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PRATT AND WHITNEY AIRCRAFT GROUP WEST PALM BEACH FL G--ETC F/G 13/9  
SURVIVABILITY OF SILICON NITRIDE BEARING.(U)

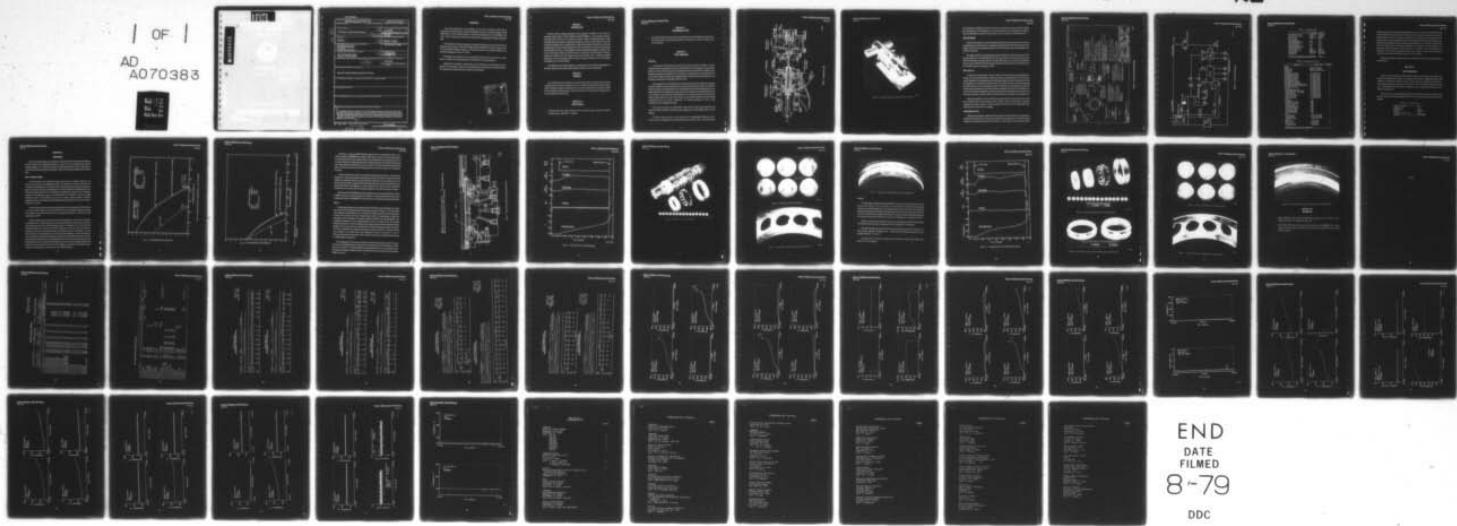
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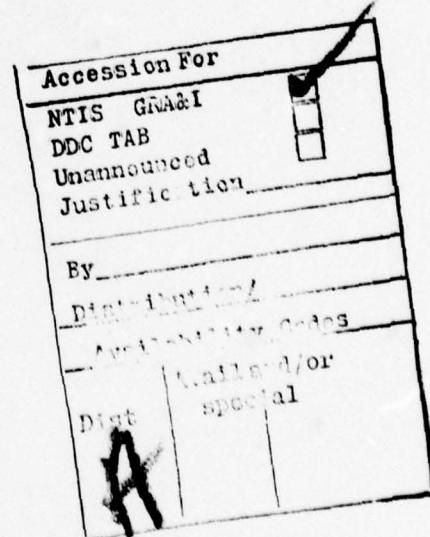
**FOREWORD**

This report describes the work performed by the Pratt & Whitney Aircraft Group, Government Products Division of United Technologies Corporation, West Palm Beach, Florida 33402 under U.S. Navy Contract N00140-77-C-0974 which incorporates U.S. Army MIPR No. RN 719-77. This is a final report covering work conducted from 1 August 1977 through 1 December 1978.

The Government technical manager for this program was Raymond Valori of the Naval Air Propulsion Center, Trenton, New Jersey 08628 (telephone (609) 882-1414). Walt Thompson of the U.S. Army Ballistic Research Laboratory, Aberdeen Proving Ground, Maryland 21005 was the technical representative for the U.S. Army.

The program was conducted at Pratt and Whitney Aircraft under the direction of John Miner, Component Technology Manager and William Grace, Program Manager.

Appreciation is extended to the following Pratt and Whitney Aircraft personnel for their assistance on this program. Jorge Alcorta and Edward Kichura assisted in the analytical effort. The experimental bearing tests were conducted by James Mohn.



**SECTION I**  
**INTRODUCTION**

Previous ceramic bearing development work sponsored at P&WA by the Naval Air Propulsion Center under Contract N00140-75-C-0382 (Reference 1) was primarily aimed at evaluating silicon nitride as a low mass ball material to offset the detrimental effect of high centrifugal ball loads expected of high speed bearings in future gas turbine engines. The results of tests with bearings with hot pressed silicon nitride rolling elements compared to an all-metal bearing showed 10 to 20% lower heat generation, 30% less axial load at the inception of ball skid, and an apparent reduction in ball temperature. These characteristics suggested a longer survival time for the ceramic bearing in situations where the lubricant flow had stopped. Should an aircraft lose lubricant flow, the bearing survival time becomes crucial to finding a suitable landing site. It is in this situation that the ceramic bearing is believed to offer a survivability advantage over an all metal bearing.

The objective of the present program is to determine the survivability characteristics of bearings containing silicon nitride balls compared to those of an all metal bearing.

**SECTION II**  
**SUMMARY**

An oil shutoff test was conducted on a 35 mm bearing with silicon nitride balls. The time to bearing failure was 90 sec compared to 45 sec for an M-50 steel bearing which was similarly tested. This result compares favorably with the 1.74 factor as predicted by an analytical model. Post-test inspection found the silicon nitride balls with minor surface distress compared to the extreme spalling of the M-50 balls.

**SECTION III**  
**CONCLUSIONS**

1. A bearing with silicon nitride elements will survive longer under conditions of lubricant starvation than an all M-50 steel bearing.

**SECTION IV**  
**RECOMMENDATIONS**

1. An optimized ball bearing with silicon nitride elements should be designed and tested in the 100-165 mm range to assess the characteristics of a bearing more suited for an engine main shaft application.

**SECTION V**  
**TEST HARDWARE**

**TEST RIG**

A cross section of the bearing test rig with the drive turbine is shown in Figure 1. A roller bearing inner race was installed as a spacer to locate the silicon nitride bearing at the proper axial position in the rig. A bearing preload of approximately 90 lb was obtained by recording critical bearing and assembly dimensions and by machining the shaft spacers to a dimension that was shorter than the distance between the housing shoulders. Additional axial load was applied to the bearings by pressuring the diaphragm (load to the left).

Oil was supplied to the test bearing from a probe that jetted oil into the shaft bore under the bearing. Channels in the shaft pumped oil to the annuli that fed the ball contact and cage land lubrication holes in the bearing inner race. Oil was supplied to the steel slave bearing by a jet (not shown) directed into the axial scoop on the rig drive shaft. Channels in the shaft pumped the oil from the scoop to annuli under the bearing inner race, which were similar to those for the test bearing. Slinger-type seals on the shaft inboard of each bearing separated the ball bearing compartments from the central compartment. The bearing discharge oil flows of each compartment were scavenged separately.

The test rig was driven by a radial inflow steam turbine through a small diameter quill shaft. The shaft is capable of absorbing small misalignments without adding load to the test bearing.

The drive turbine assembly is self-contained with an independent lubrication system. Figure 2 shows a photograph of the assembled bearing rig and drive turbine. The bearing rig is

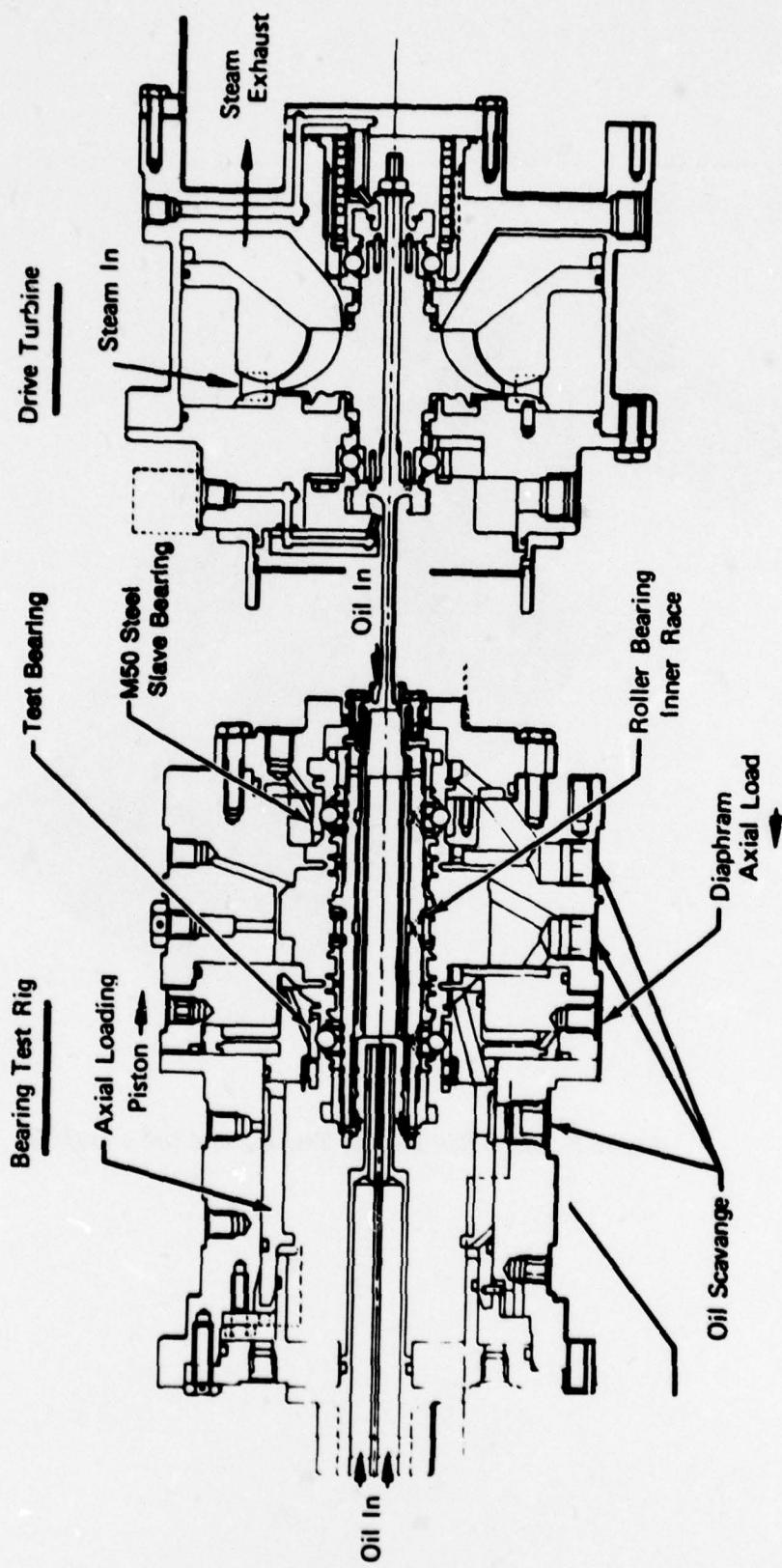
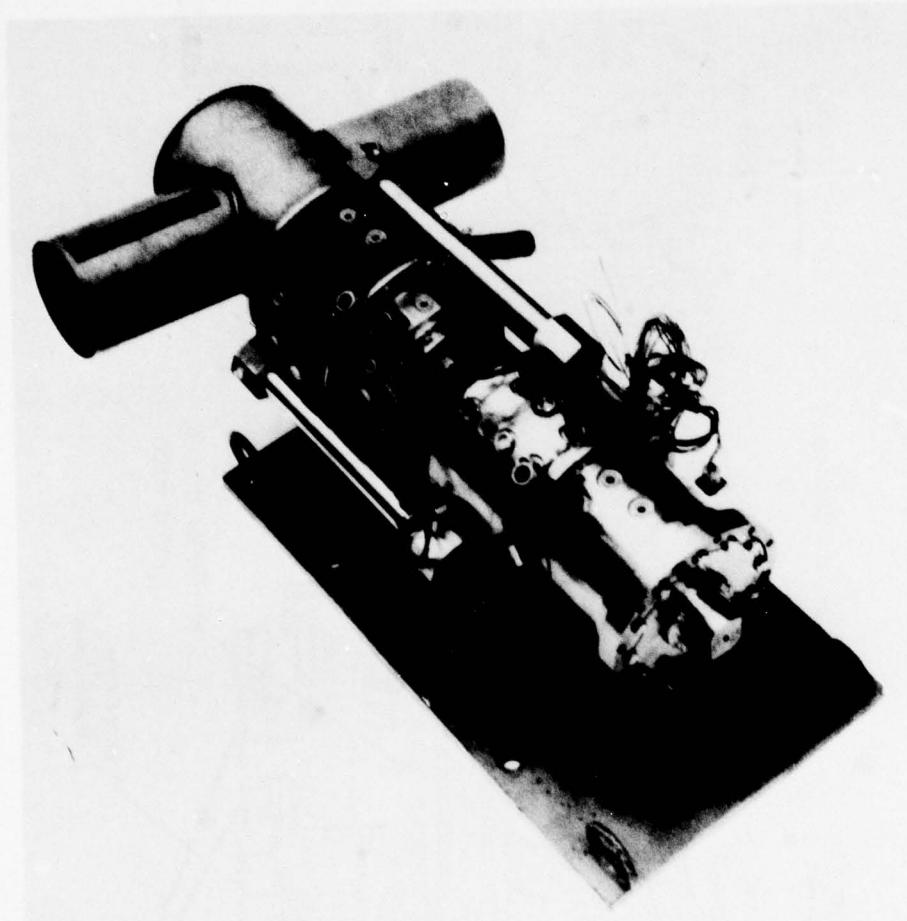


Figure 1. Bearing Test Rig

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*Figure 2. Assembled Bearing Test Rig and Drive Turbine*

hard mounted to a baseplate and the drive turbine is supported from three pins which extend from the bearing rig. Three bushings on the drive turbine allow the turbine assembly to slide on the pins preventing the transfer of axial load from the drive turbine to the bearing test rig.

### TEST BEARINGS

A 35 mm bore angular contact ball bearing having M-50 tool steel races and Norton NC132 hot pressed silicon nitride balls, and a comparable bearing with M-50 steel balls were used in the program. The silicon nitride bearing is identical to the steel bearing, which was designed for a 2.5 million DN operation.

The design of the silicon nitride bearing is shown in Figure 3. The bearing inner race is split and contains grooves in the unloaded half for ball contact lubrication. Holes are provided in the lands for lubrication of the cage journals. The cage which rides on the inner land, was machined from one piece of AMS 6414 and silver plated. Design details for the silicon nitride bearing, and for the steel bearing, are presented in Table I.

### TEST FACILITY

A schematic of the test facility is shown in Figure 4. Oil was pumped from a 25 gal reservoir through a  $10\mu$  filter and distributed to both test and slave rig bearings as well as to the drive turbine bearings. Oil for pressurization of the bearing load piston was also pumped from the tank and supplied to the rig through individual control valves. The test, slave, and turbine bearings had individual flow control valves and flow meters. In addition, the test bearing oil supply line had an electrically operated on-off solenoid valve for stopping the oil flow to the test bearing. The oil from each bearing compartment was scavenged with individual pumps and returned to the tank through a water-oil cooler. A steam coil was immersed in the oil reservoir for heating the oil.

Steam was supplied to the drive turbine from an area system through a large control valve and a parallel vernier valve for precise control of speed. The steam supply had a manually operated abort system to prevent a turbine overspeed in the event of a drive shaft failure when bearing seizure occurred after oil stoppage.

### INSTRUMENTATION

Bearing instrumentation, listed in Table II, was identical for each bearing in both the silicon nitride and steel bearing tests. Outer race temperature was measured with four thermocouples installed in each bearing housing so that they were in contact with the outer races. Axial load was

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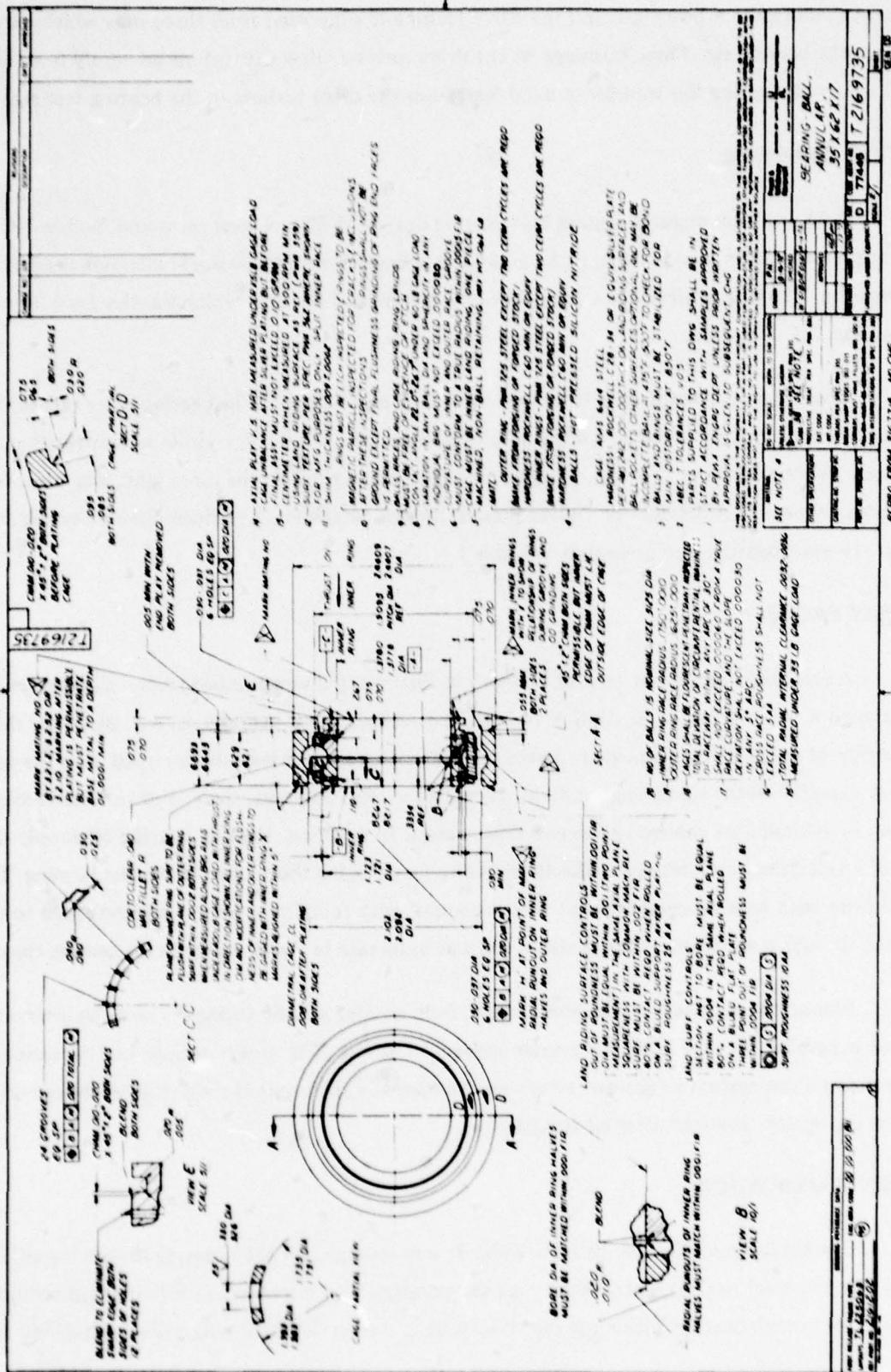


Figure 3. Silicon Nitride Bearing Design

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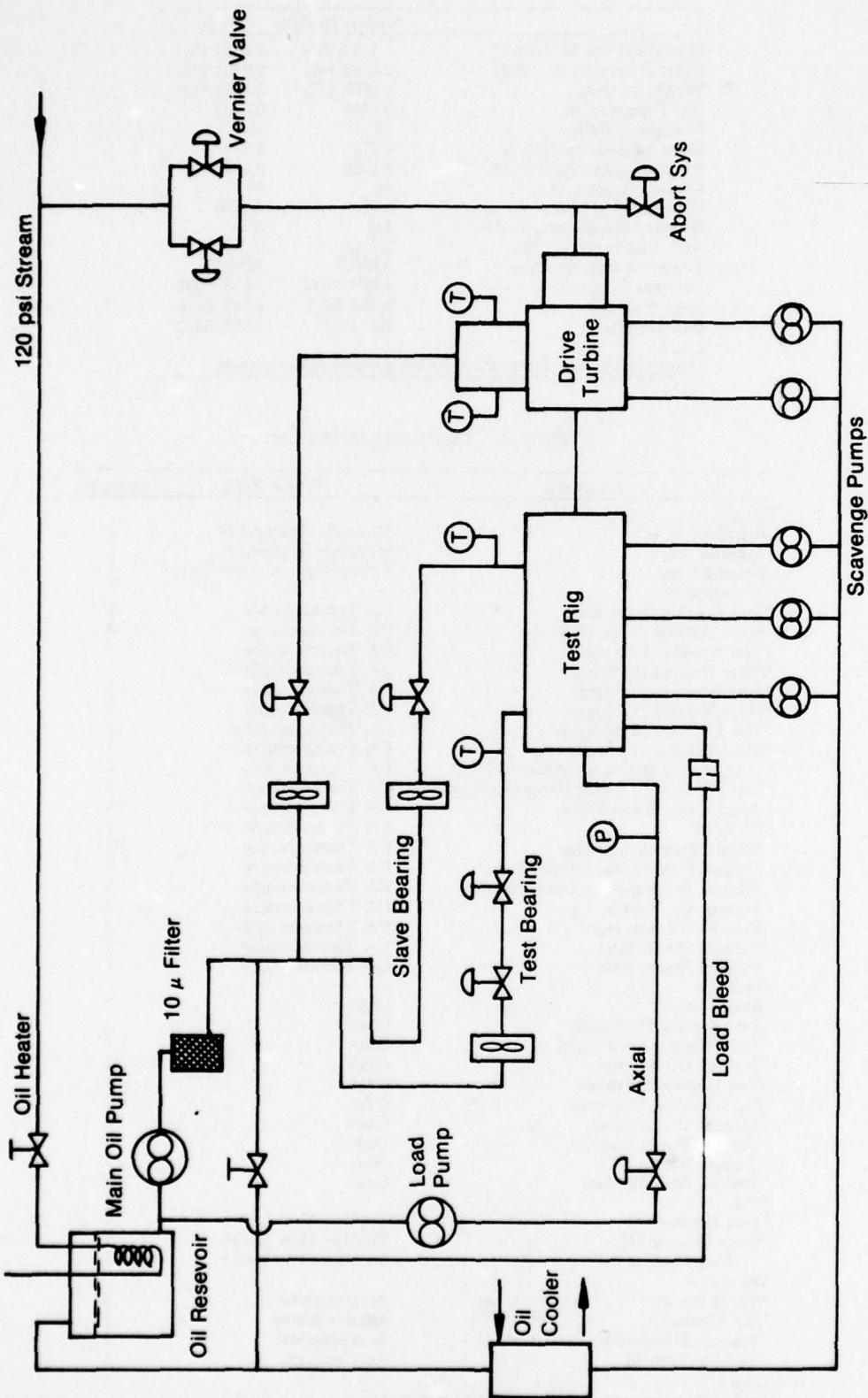


Figure 4. Test Facility Schematic

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*Table I. Bearing Design*

|                           | <i>Silicon Nitride</i> | <i>M-50</i> |
|---------------------------|------------------------|-------------|
| Bore Diameter, in. (mm)   | 1.3780 (35)            | 1.3780 (35) |
| Outer Diameter, in. (mm)  | 2.4409 (62)            | 2.4408 (62) |
| Width, in. (mm)           | 0.6690 (17)            | 0.6679 (17) |
| Ball Diameter, in.        | 0.3119                 | 0.3127      |
| Number of Balls           | 15                     | 15          |
| Inner Raceway Radius, in. | 0.175                  | 0.175       |
| Outer Raceway Radius, in. | 0.1625                 | 0.1625      |
| Contact Angle, deg        | 25                     | 25          |
| Diametral Clearance, in.  | 0.0036                 | 0.0036      |
| Raceway Roughness, in. AA | 4-6                    | 4-5         |
| Ball Roughness, in. AA    | 2.5-3.3                | 2.3-3.0     |
| Tolerance Specification   | ABEC7                  | ABEC7       |
| Raceway Material          | AMS 6490               | AMS 6490    |
| Cage Material             | AMS 6414               | AMS 6414    |
| Ball Material             | NC 132*                | AMS 6490    |

\*Norton Company designation for hot pressed silicon nitride.

*Table II. Instrumentation List*

| <i>Parameter</i>                        | <i>Sensor Type</i>        | <i>Quantity</i> |
|---|---------------------------|-----------------|
| <i>Speeds</i>                           |                           |                 |
| Rig Shaft                               | Magnetic Transducer       | 1               |
| Turbine Shaft                           | Magnetic Transducer       | 1               |
| Bearing Cage                            | Strain Gage on Outer Race | 1               |
| <i>Temperatures</i>                     |                           |                 |
| *Test Bearing Outer Race                | CA Thermocouple           | 4               |
| Slave Bearing Outer Race                | CA Thermocouple           | 4               |
| *Test Bearing Oil Supply                | CA Thermocouple           | 1               |
| *Slave Bearing Oil Supply               | CA Thermocouple           | 1               |
| *Test Bearing Oil Sump                  | CA Thermocouple           | 2               |
| *Slave Bearing Oil Sump                 | CA Thermocouple           | 2               |
| *Test Bearing Oil Scavenge              | CA Thermocouple           | 1               |
| *Slave Bearing Oil Scavenge             | CA Thermocouple           | 1               |
| *Test Bearing Air Temp Puller Groove    | CA Thermocouple           | 2               |
| *Test Bearing Air Temp Nonpuller Groove | CA Thermocouple           | 2               |
| *Internal Rig Metal Temp.               | CA Thermocouple           | 14              |
| Oil Tank                                | CA Thermocouple           | 1               |
| Middle Bearing Scavenge                 | CA Thermocouple           | 1               |
| Turbine Bearing No. 1 Outer Race        | CA Thermocouple           | 2               |
| Turbine Bearing No. 2 Outer Race        | CA Thermocouple           | 2               |
| Turbine Oil Supply                      | CA Thermocouple           | 2               |
| Turbine Oil Scavenge                    | CA Thermocouple           | 2               |
| Turbine Steam Inlet                     | CA Thermocouple           | 1               |
| Turbine Steam Exit                      | CA Thermocouple           | 1               |
| <i>Pressures</i>                        |                           |                 |
| Axial Load                              | Gage                      | 1               |
| Test Bearing Oil Supply                 | Gage                      | 1               |
| Slave Bearing Oil Supply                | Gage                      | 1               |
| Turbine Oil Supply                      | Gage                      | 1               |
| Test Bearing Scavenge                   | Gage                      | 1               |
| Slave Bearing Scavenge                  | Gage                      | 1               |
| Turbine Oil Scavenge                    | Gage                      | 1               |
| Turbine Steam Supply                    | Gage                      | 1               |
| Turbine Steam Exit                      | Gage                      | 1               |
| Turbine Seal Air Dam                    | Gage                      | 2               |
| <i>Flows</i>                            |                           |                 |
| *Test Bearing Oil                       | Turbine Flow Meter        | 1               |
| Slave Bearing Oil                       | Turbine Flow Meter        | 1               |
| Turbine Bearing Oil                     | Turbine Flow Meter        | 1               |
| <i>Vibrations</i>                       |                           |                 |
| *Rig Horizontal                         | Accelerometer             | 2               |
| *Rig Vertical                           | Accelerometer             | 2               |
| Turbine Horizontal                      | Accelerometer             | 1               |
| Turbine Vertical                        | Accelerometer             | 1               |

\*Indicates parameter is recorded on magnetic tape.

determined as the sum of the estimated preload and the product of the pressure and the load area of the diaphragm. Thermocouples were immersed in the oil supply lines and rig sump to measure bearing supply and exit oil temperature. Cage speed was measured with strain gages on the bearing outer race, which sensed the dynamic strain resulting from ball passage. Shaft speed was measured with a magnetic transducer that sensed the passing of a 12-tooth cog on the shaft. Oil flows were measured with turbine-type flowmeters in the supply lines; rig vibrations were measured with accelerometers on the rig housing. A complete list of all instrumentation is presented in Table II; the parameters noted were also recorded on magnetic tape during the transient period when the oil flow was shut off to the test bearing.

Standards traceable to the National Bureau of Standards were used for the calibration of all instrumentation.

## SECTION VI

### TEST PROCEDURE

The test rig with the M-50 steel bearing was installed in the test facility. The oil system was serviced with approximately 25 gal of oil qualified under the MIL-L-23699B specification. Rig conditions as specified in Table III were set. After steady-state operation was achieved, a complete set of stand and rig data was recorded. The oil to the test bearing was then shut off. The time to bearing failure was recorded by a stopwatch and on magnetic tape along with other transient rig parameters.

After the test, the rig was disassembled and photographs were taken of the M-50 steel bearing. The rig was then reassembled with the silicon nitride bearing and the test program was repeated.

Table III. Test Conditions

|                                   |                   |
|-----------------------------------|-------------------|
| Oil Inlet Temperature             | 150°F             |
| Environment                       | Air               |
| Bearing Bore Size                 | 35 mm             |
| Rig Speed                         | 62,000 rpm        |
| Thrust                            | 135 lb            |
| DN (Bearing bore mm $\times$ rpm) | $2.2 \times 10^6$ |
| Lubricant                         | MIL-L-23699B      |

## **SECTION VII**

### **DISCUSSION**

The silicon nitride program was conducted in three tasks. Task I consisted of developing an analytical model of the high-speed bearing rig to predict the time to bearing seizure (loss of internal clearance) for the M-50 and the silicon nitride bearings. Task II was an oil shutoff test on an M-50 ball bearing. Task III was a repeat of Task II with a bearing containing silicon nitride balls.

#### **Task I Analytical Model**

A thermal model of the high-speed bearing rig was used to simulate conditions of oil starvation in both 35 mm bore high-speed bearings. Two different test conditions were used with the silicon nitride ball bearing. The first set of test conditions assumed a bearing heat generation based on the results of previous testing (Reference 1) which showed that the heat generation from silicon nitride balls was 89.5% of the value with M-50 balls. The second set of test conditions assumed a heat generation equal to the M-50 bearing. The theoretical criteria for bearing malfunction used in these analyses is the loss of internal running clearance. Transient temperatures from the analyses and the P&WA Bearing Analysis Deck were used to determine clearance loss vs time.

Use of the thermal model and the originally specified oil inlet temperature of 250°F resulted in a loss of internal clearance of both the M-50 and silicon nitride ball bearings in less than 5 sec. Based on the results of this study, the test program was changed to reduce the oil inlet temperature to 150°F.

Using the thermal model and reducing the oil inlet temperature to 150°F prior to oil shutoff, the predicted time to bearing seizure due to loss of internal clearance was 43 sec for the silicon nitride bearing and 25 sec for the M-50 bearing (Figure 5). In addition to the time until loss of internal clearance, two other points are worthy of mention on this curve. One, the lower heat generation of the silicon nitride bearing did not significantly improve survivability. Two, the major contributor to the improvement in survivability was the difference in thermal expansion of the two materials. Although both bearings have the same internal clearance when cold, at steady-state operating conditions the silicon nitride bearing has nearly twice the internal clearance of the M-50 bearing. If both bearings had been designed to have the same operating clearance (see Figure 6), the silicon nitride, because of its lower coefficient of expansion, would still provide a benefit (35% improvement) in survivability over the M-50 steel ball.

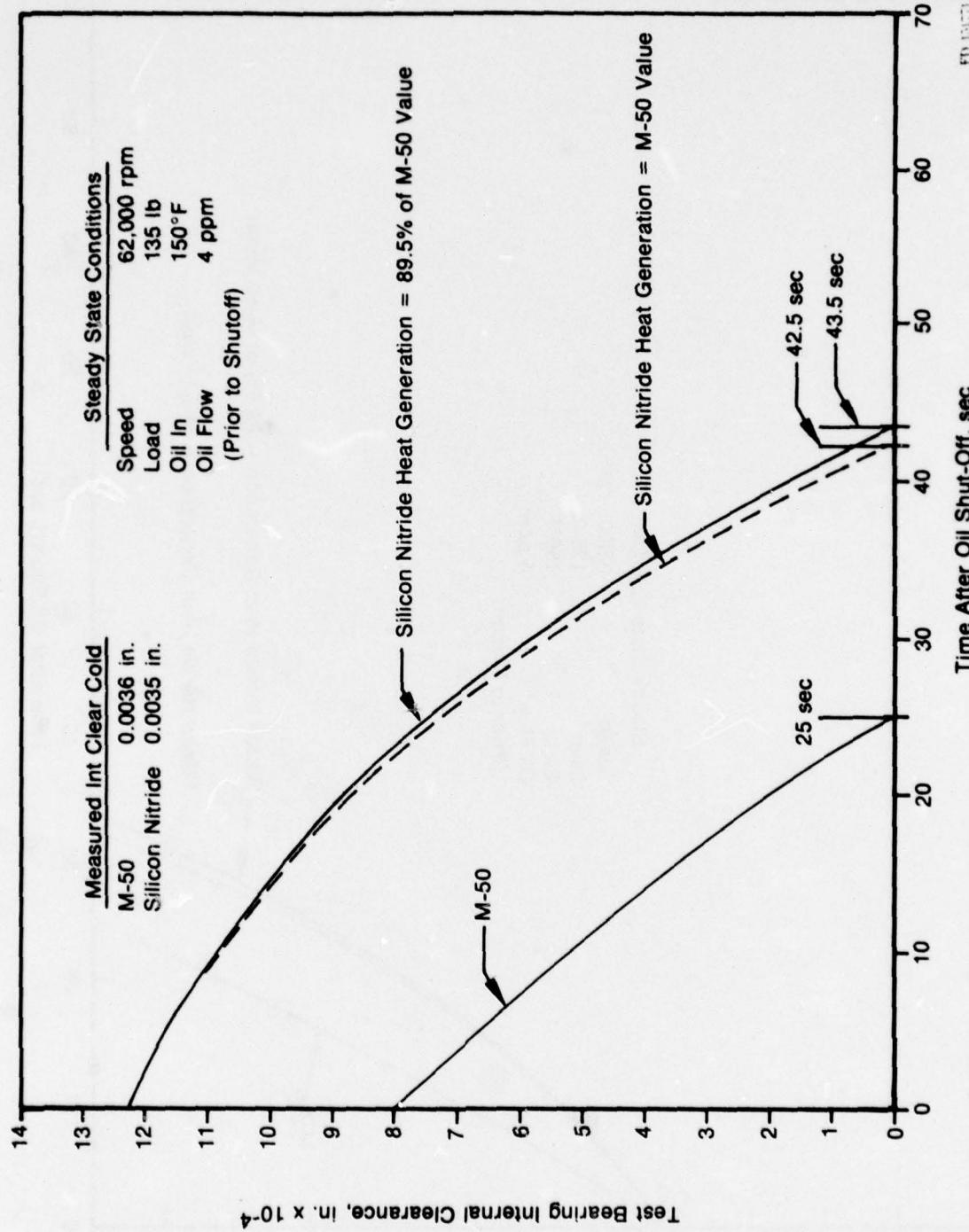


Figure 5. Analytical Prediction of Bearing Seizure After Oil Shutoff

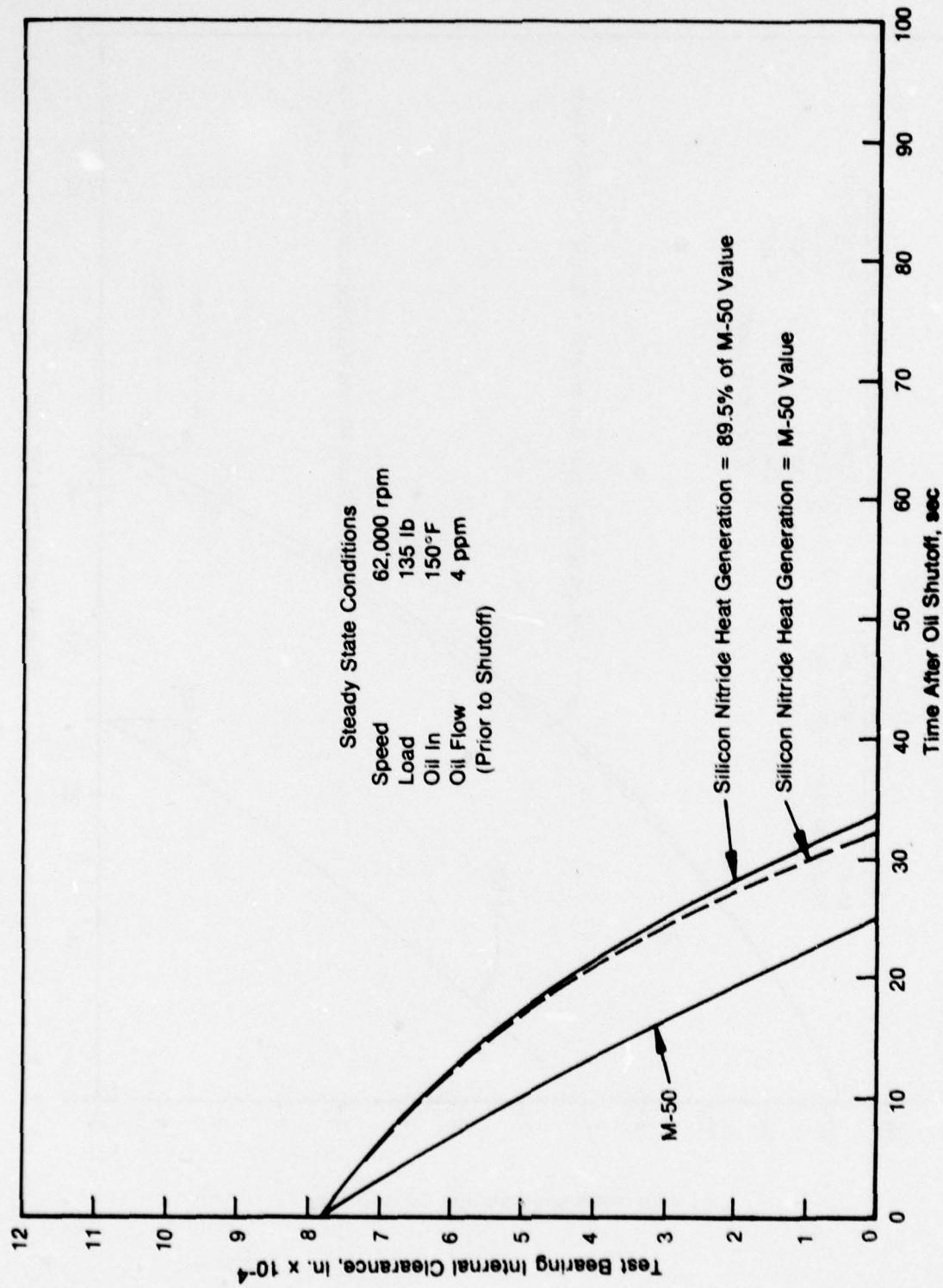


Figure 6. Analytical Prediction of Bearing Seizure After Oil Shut-off Assuming Both Bearings Have the Same Internal Clearance at Steady-State

In addition to using the P&WA Bearing Analysis Deck, an attempt was made to use a computer program (SHABERTH) developed by SKF under contract to the Air Force (Reference 2) to analytically simulate the combined effects of bearing kinematics and thermal behavior of an oil-starved bearing in the high-speed bearing rig. Separate analyses were conducted for bearings with rolling elements of M-50 steel and silicon nitride. The analytical predictions showed that failure would occur faster for the M-50 bearing than with the silicon nitride, but the difference was slight.

A steady-state thermal analysis was undertaken using test data obtained in a previous test (Reference 1). The thermal response corresponded well with the test data. The M-50 or  $\text{Si}_3\text{N}_4$  test steady-state temperature map was used for the initial conditions for the oil starvation runs. The results of the oil starvation analyses exhibited excessive heat generation and temperature rise for the starvation factors used (Reference 2), when compared to the current test data. Subsequent modifications to the model created convergence problems in the starvation region of interest.

Problems with the SHABERTH computer program were noted upon installation of the deck at P&WA, as well as in various variations in the model. It is recommended that further work in correlating this data with SHABERTH be done to reduce the convergence problems experienced.

## Task II

The high-speed bearing rig was assembled with an M-50 slave and test bearing. An enlarged view of the test section showing internal instrumentation is shown in Figure 7. A 5-minute steady-state condition was established at the test conditions of 62,000 rpm and an oil inlet temperature of 150°F. The oil was shut off with a solenoid valve located in the test bearing oil supply line. Immediately after oil stoppage, the rig speed climbed to 72,000 rpm and the bearing outer race temperature increased at a rate of approximately 2.4°F per sec. After 45 sec, the rig speed dropped instantly from 72,000 to 30,000 rpm and all vibration meters showed maximum full scale readings. At this point the test was terminated by activating the steam abort system. The results of this test, as taken from the magnetic tape system, are shown in Figure 8. At the point the test was terminated, the bearing outer race temperature started to increase at a rate of 35°F per sec and reached a maximum of 425°F. The test rig was then removed from the test stand and disassembled for inspection.

Upon disassembly of the rig, severe distress of the M-50 test bearing was noticed. The inner race halves were welded together. In trying to pull one half of the inner race off the shaft, the other came with it (Figure 9). The balls exhibited severe spalling (Figure 10). (The dark spots on the photographs are shadows of adjacent balls.) The cage and outer race showed much metal transfer (Figures 11 and 12).

■ Metal Temperatures (At 90° and 270° Locations)  
● Environment Temperatures (At 90° and 270° Locations)

Transient Monitoring

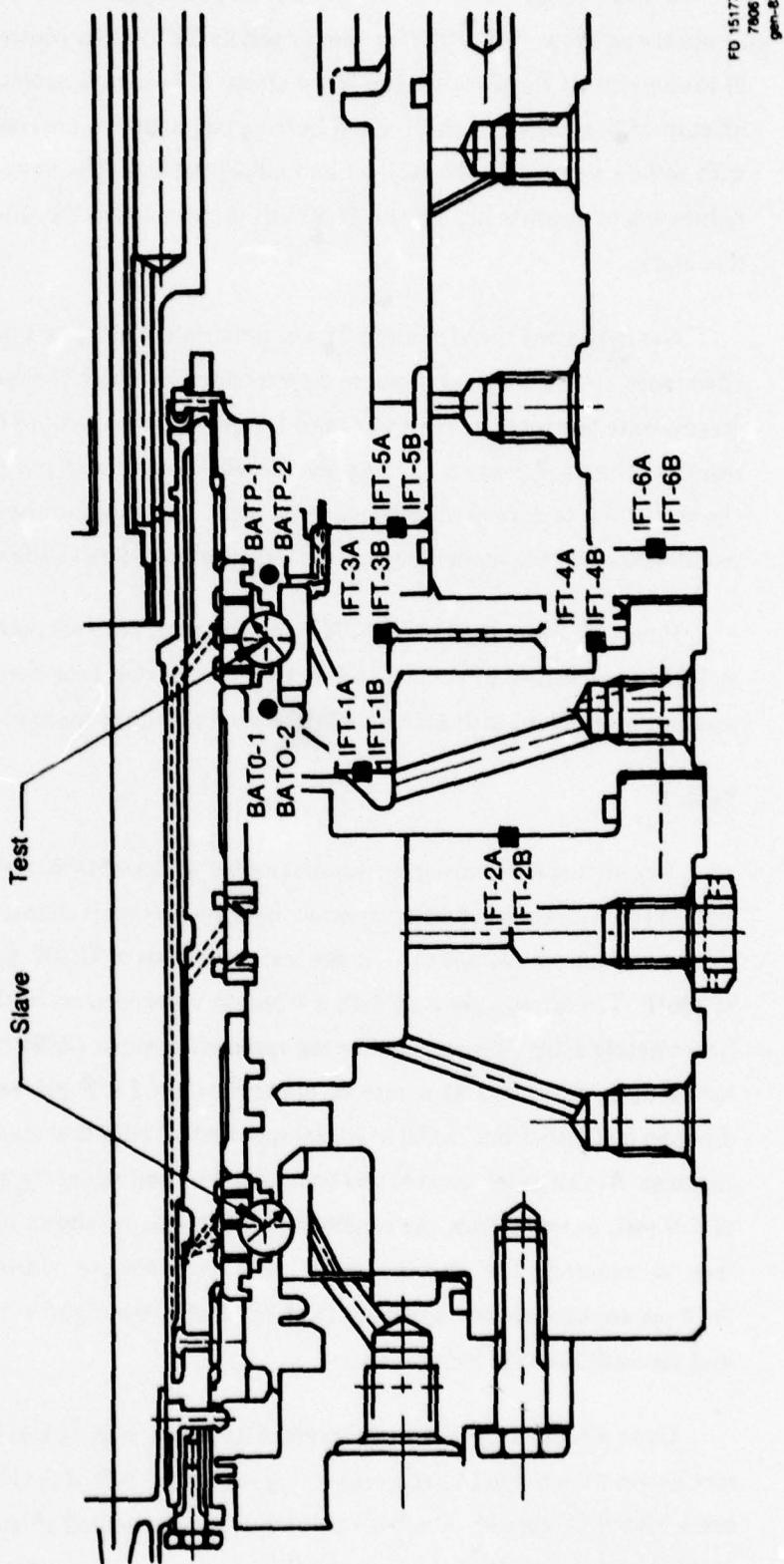


Figure 7. Temperatures Monitored During Shutoff Test

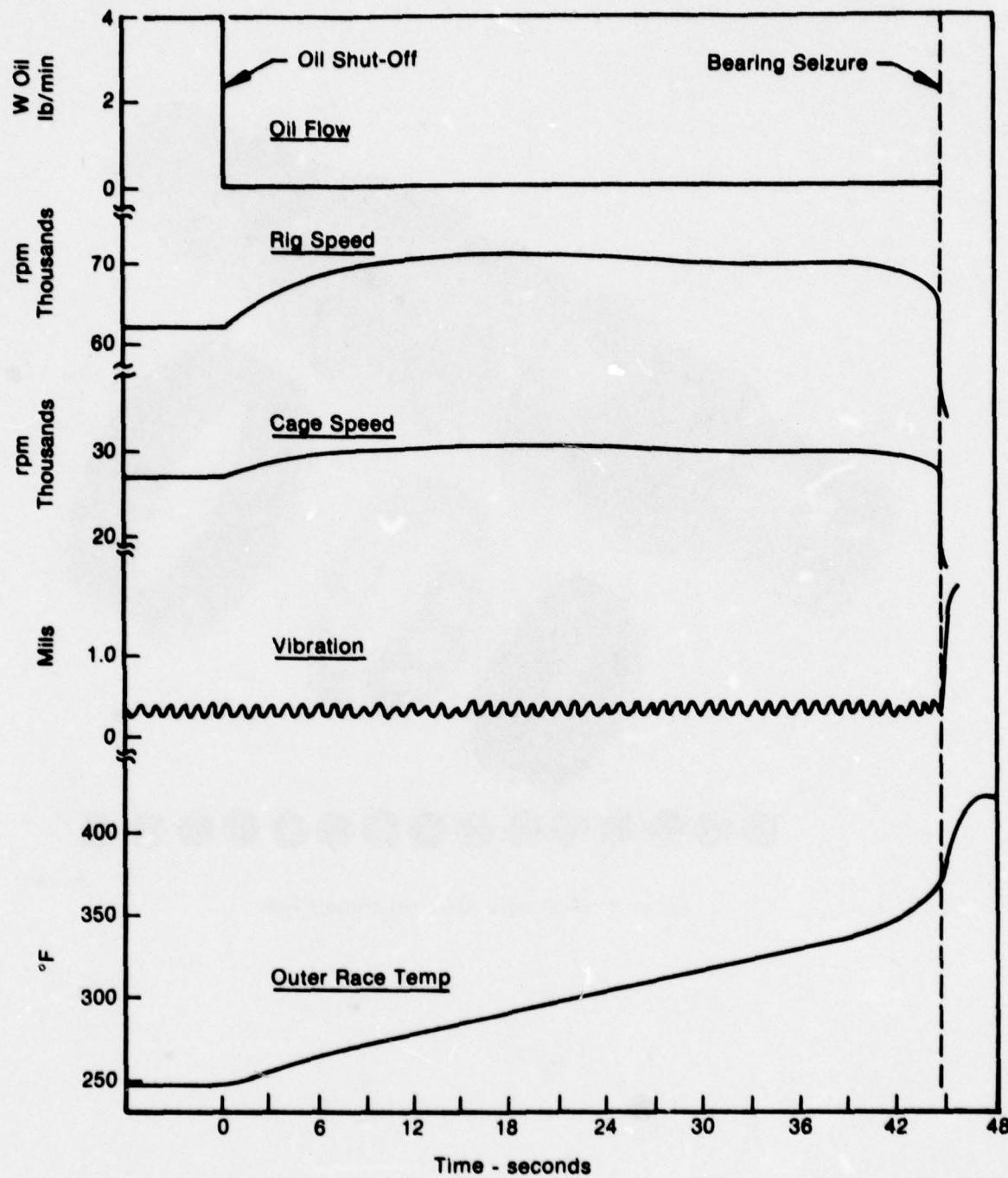


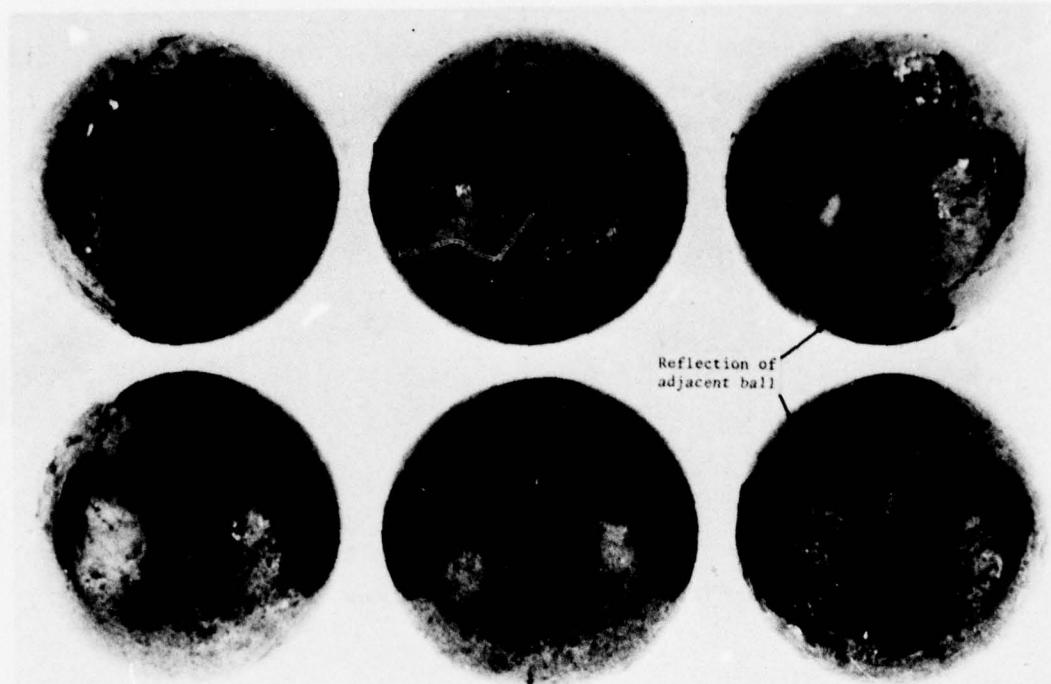
Figure 8. Oil Shutoff Test, M-50 Ball Bearing

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Figure 9. M-50 Balls After Oil Shutoff Test



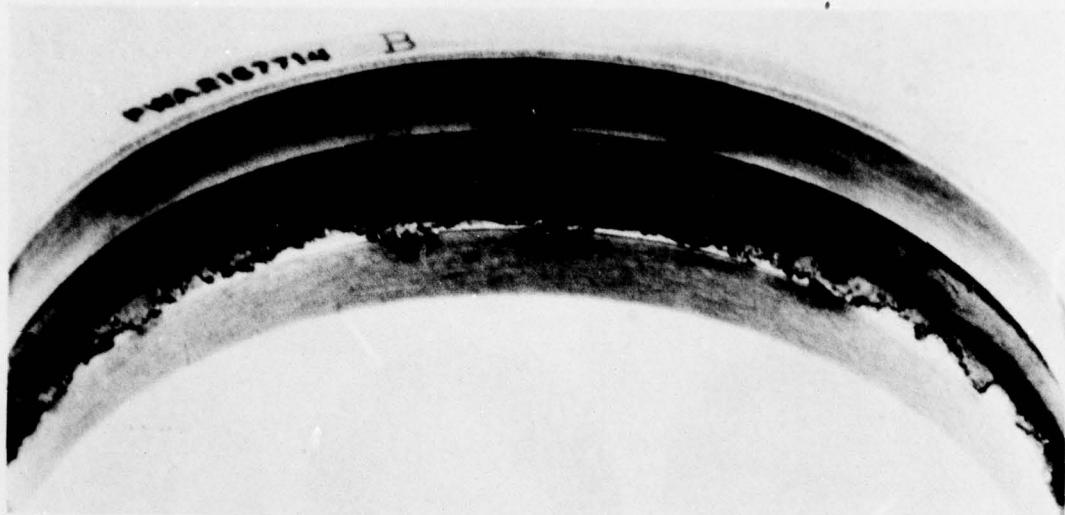
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Figure 10. M-50 Balls After Oil Shutoff Test



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Figure 11. Outer Race of M-50 Bearing After Oil Shutoff Test



*Figure 12. Outer Race of M-50 Bearing After Oil Shutoff Test*

### **Task III**

The high-speed bearing rig was reassembled with a silicon nitride ball bearing in the test position and returned to the test facility. A 5-min steady-state condition was established identical to the M-50 bearing prior to oil stoppage. After oil shutoff, the silicon nitride bearing produced similar speed and vibration indications as the M-50, but time to failure was increased to 90 sec. The data from the magnetic tape (Figure 13) show almost identical trends except that the outer race temperature increased at a rate of only 1.8 deg per sec to a maximum of 420°F.

Inspection of the bearing revealed that the silicon nitride bearing suffered much less distress than the M-50 bearing. Figures 14 through 18 show the conditions of the bearings.

The results of these tests show that the silicon nitride bearing survived twice as long as the M-50 bearing. Although the absolute time is different than the analytical model, this ratio compares favorably (1.74 vs 2.0).

A complete list of all data, and graphs of all transient data taken during Task II and Task III are in the Appendix.

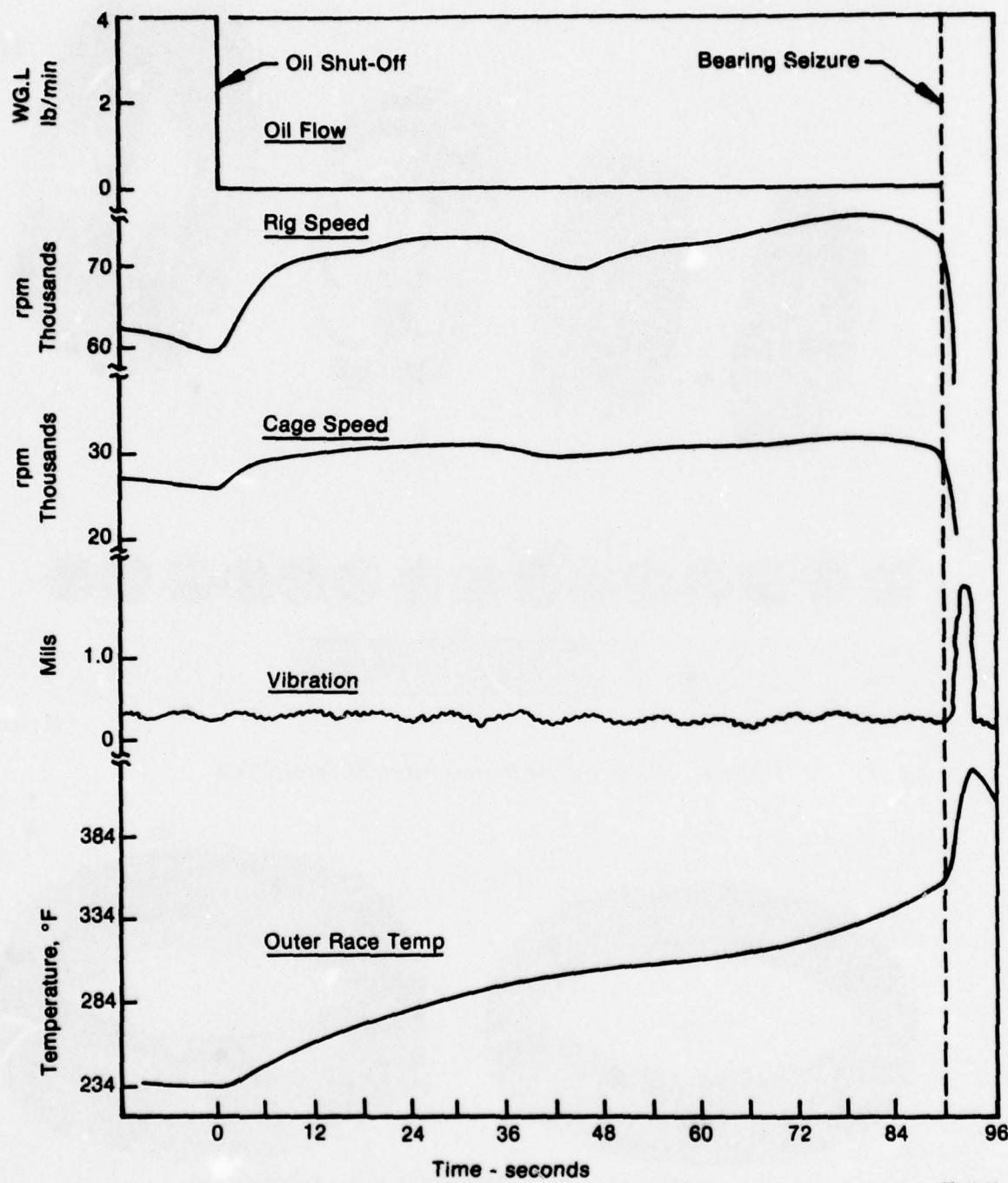
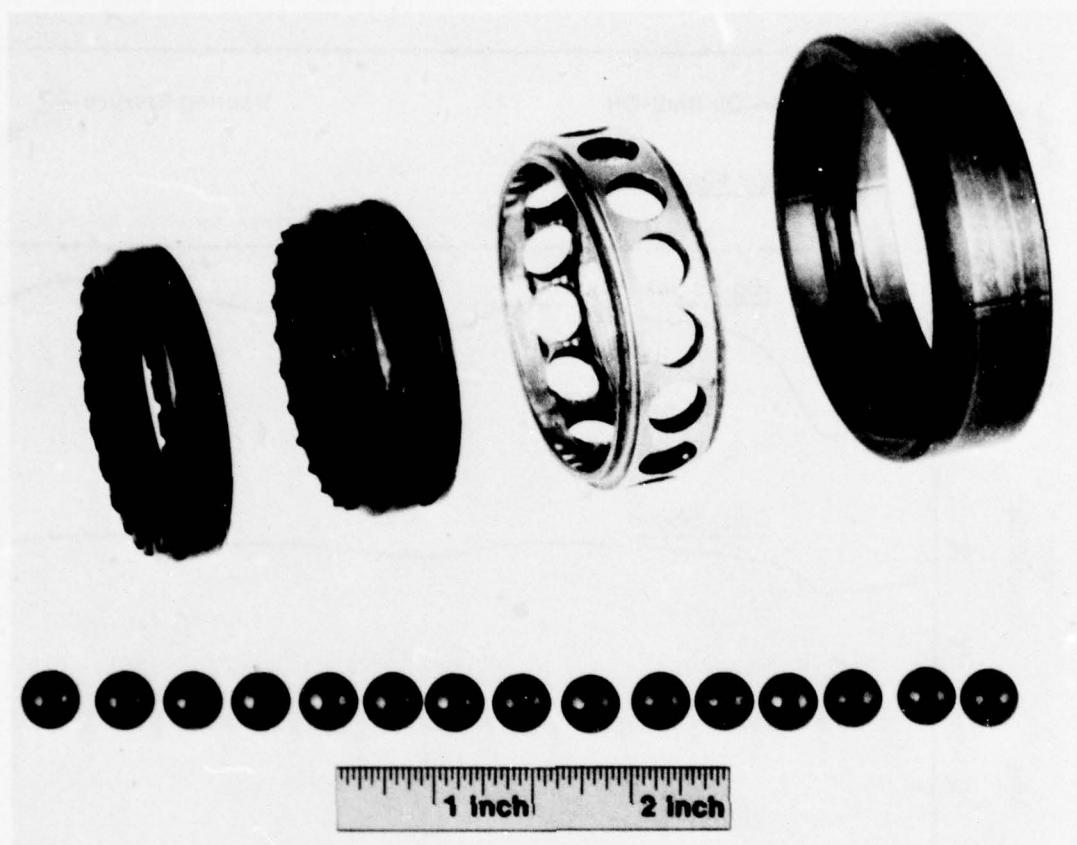
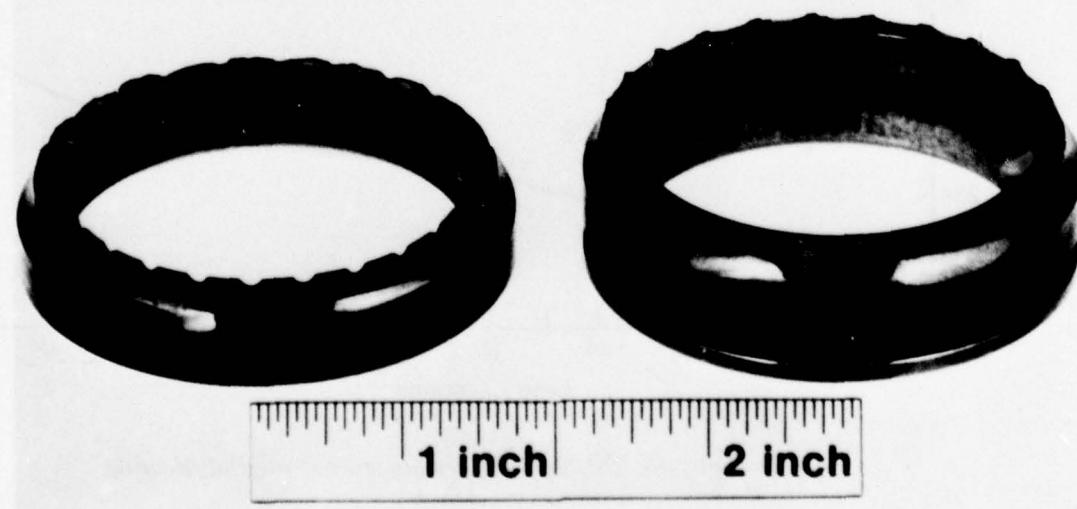


Figure 13. Oil Shutoff Test Silicon Nitride Ball Bearing



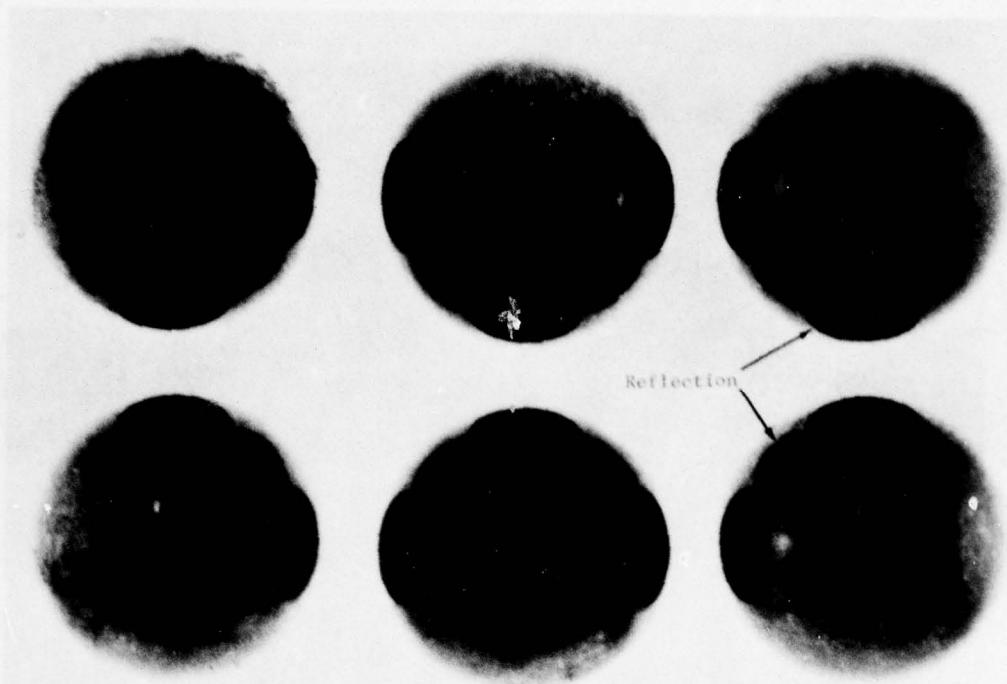
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Figure 14. Silicon Nitride Bearing After Oil Shutoff Test



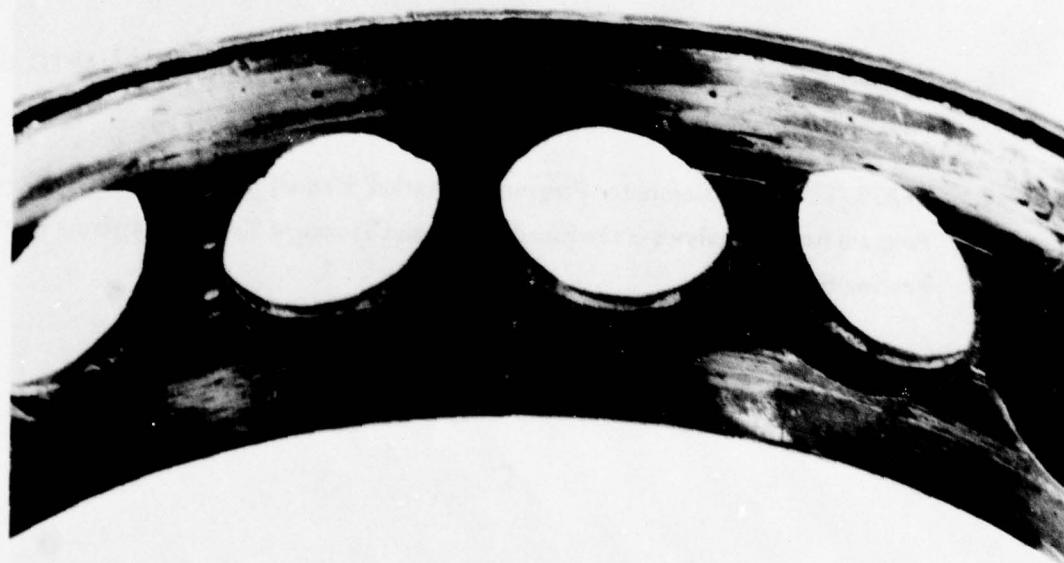
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Figure 15. Inner Race of Silicon Nitride Bearing After Oil Shutoff Test



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Figure 16. Silicon Nitride Balls After Oil Shutoff Test



FE 168188

Figure 17. Cage of Silicon Nitride Bearing After Oil Shutoff Test



*Figure 18. Outer Race of Silicon Nitride Bearing After Oil Shutoff Test*

**SECTION VIII**  
**REFERENCES**

1. Report FR-6995 "Silicon Nitride Ball Bearing Demonstration Test," NAPTC Contract N00140-75-C-0382, J. M. Reddcliff, 10 May 1975.
2. AFAPL-TR-76-90 "Computer Program Operation Manual on SHABERTH: A Computer Program for the Analyses of the Steady State and Transient Thermal Performance on Shaft Bearing Systems."

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APPENDIX

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Original Date 12 Oct 1977  
Revised Date 7 Mar 1978

**INSTRUMENTATION SCHEDULE**

| Engine/Rig No.                         | F-38846-7 | Type      | High Speed Brdg. Rig | Rig         | Test of           | Oil Starvation-SIN Ball Brdg. |      |         |       |              |         |
|--|-----------|-----------|----------------------|-------------|-------------------|-------------------------------|------|---------|-------|--------------|---------|
| Stand                                  | D-3       | Build No. | 6                    | 6           | Test Engineer     | J. Mohn                       |      |         |       |              |         |
| Work Order No.                         |           | Run Date  | 3 Apr 1978           |             | Alt Test Engineer | B. Grace                      |      |         |       |              |         |
| Recording and Readout Required         |           |           |                      |             |                   |                               |      |         |       |              |         |
| Item Description                       | Header    | Range     | Accuracy             | Environment | TC Type           | Gage                          | D DR | O-Graph | Meter | Strip Charts | Remarks |
| <b>Rig Temperatures</b>                |           |           |                      |             |                   |                               |      |         |       |              |         |
| Test Brdg. No.1 Outer Race Temp.       | BRT1-1    | Amb.100°F | ±5°F                 | Oil         | C/A               |                               |      |         |       |              | Doric   |
| Test Brdg. No.1 Outer Race Temp.       | BRT1-2    | Amb.100°F | ±5°F                 | Oil         | C/A               |                               |      |         |       |              | Doric   |
| Test Brdg. No.1 Outer Race Temp.       | BRT1-3    | Amb.100°F | ±5°F                 | Oil         | C/A               |                               |      |         |       |              | Doric   |
| Test Brdg. No.1 Outer Race Temp.       | BRT1-4    | Amb.100°F | ±5°F                 | Oil         | C/A               |                               |      |         |       |              | Doric   |
| Test Brdg. No.1 Oil Sump Temp.         | BOST1-1   | Amb.100°F | ±5°F                 | Oil         | C/A               |                               |      |         |       |              | Doric   |
| Test Brdg. No.1 Oil Sump Temp.         | BOST1-2   | Amb.100°F | ±5°F                 | Oil         | C/A               |                               |      |         |       |              | Doric   |
| Test Brdg. No.1 Scavenging Temp.       | BOOTT1    | Amb.100°F | ±5°F                 | Oil         | C/A               |                               |      |         |       |              | Doric   |
| Test Brdg. No.1 Oil Supply Temp.       | BOOTT1    | Amb.100°F | ±5°F                 | Oil         | C/A               |                               |      |         |       |              | Doric   |
| Test Brdg. No.2 Outer Race Temp.       | BRT2-1    | Amb.100°F | ±5°F                 | Oil         | C/A               |                               |      |         |       |              | Doric   |
| Test Brdg. No.2 Outer Race Temp.       | BRT2-2    | Amb.100°F | ±5°F                 | Oil         | C/A               |                               |      |         |       |              | Doric   |
| Test Brdg. No.2 Outer Race Temp.       | BRT2-3    | Amb.100°F | ±5°F                 | Oil         | C/A               |                               |      |         |       |              | Doric   |
| Test Brdg. No.2 Outer Race Temp.       | BRT2-4    | Amb.100°F | ±5°F                 | Oil         | C/A               |                               |      |         |       |              | Doric   |
| Test Brdg. No.2 Oil Sump Temp.         | BGSST2-1  | Amb.100°F | ±5°F                 | Oil         | C/A               |                               |      |         |       |              | Doric   |
| Test Brdg. No.2 Oil Supply Temp.       | BGSST2-2  | Amb.100°F | ±5°F                 | Oil         | C/A               |                               |      |         |       |              | Doric   |
| Test Brdg. No.2 Scavenging Temp.       | BOOTT2    | Amb.100°F | ±5°F                 | Oil         | C/A               |                               |      |         |       |              | Doric   |
| Test Brdg. No.2 Oil Supply Temp.       | BOOTT2    | Amb.100°F | ±5°F                 | Oil         | C/A               |                               |      |         |       |              | Doric   |
| Test Brdg. No.2 Air Temp. Puller Gr've | BATP-1    | Amb.100°F | ±5°F                 | Oil         | C/A               |                               |      |         |       |              | Doric   |
| Test Brdg. No.2 Air Temp. Puller Gr've | BATP-2    | Amb.100°F | ±5°F                 | Oil         | C/A               |                               |      |         |       |              | Doric   |
| Test Brdg. No.2 Air Temp. Oil Groove   | BATO-1    | Amb.100°F | ±5°F                 | Oil         | C/A               |                               |      |         |       |              | Doric   |
| Test Brdg. No.2 Air Temp. Oil Groove   | BATO-2    | Amb.100°F | ±5°F                 | Oil         | C/A               |                               |      |         |       |              | Doric   |
| Interface Temp. 1A                     | IFT-1A    | Amb.100°F | ±5°F                 | Oil         | C/A               |                               |      |         |       |              | Doric   |
| Interface Temp. 1B                     | IFT-1B    | Amb.100°F | ±5°F                 | Oil         | C/A               |                               |      |         |       |              | Doric   |
| Interface Temp. 2A                     | IFT-2A    | Amb.100°F | ±5°F                 | Oil         | C/A               |                               |      |         |       |              | Doric   |
| Interface Temp. 2B                     | IFT-2B    | Amb.100°F | ±5°F                 | Oil         | C/A               |                               |      |         |       |              | Doric   |
| Interface Temp. 3A                     | IFT-3A    | Amb.100°F | ±5°F                 | Oil         | C/A               |                               |      |         |       |              | Doric   |
| Interface Temp. 3B                     | IFT-3B    | Amb.100°F | ±5°F                 | Oil         | C/A               |                               |      |         |       |              | Doric   |
| Interface Temp. 4A                     | IFT-4A    | Amb.100°F | ±5°F                 | Oil         | C/A               |                               |      |         |       |              | Doric   |
| Interface Temp. 4B                     | IFT-4B    | Amb.100°F | ±5°F                 | Oil         | C/A               |                               |      |         |       |              | Doric   |
| Interface Temp. 5A                     | IFT-5A    | Amb.100°F | ±5°F                 | Oil         | C/A               |                               |      |         |       |              | Doric   |
| Interface Temp. 5B                     | IFT-5B    | Amb.100°F | ±5°F                 | Oil         | C/A               |                               |      |         |       |              | Doric   |
| Interface Temp. 6A                     | IFT-6A    | Amb.100°F | ±5°F                 | Oil         | C/A               |                               |      |         |       |              | Doric   |
| Interface Temp. 6B                     | IFT-6B    | Amb.100°F | ±5°F                 | Oil         | C/A               |                               |      |         |       |              | Doric   |
| Flex Plate Temp.                       | FPT-1     | Amb.100°F | ±5°F                 | Oil         | C/A               |                               |      |         |       |              | Doric   |
| Flex Plate Temp.                       | FPT-2     | Amb.100°F | ±5°F                 | Oil         | C/A               |                               |      |         |       |              | Doric   |
| Oil Tank Temp.                         | OTT       | Amb.100°F | ±5°F                 | Oil         | C/A               |                               |      |         |       |              | Doric   |
| Middle Big. Compartment Scav. Temp.    | MBOOT     | Amb.100°F | ±5°F                 | Oil         | C/A               |                               |      |         |       |              | Doric   |

## INSTRUMENTATION SCHEDULE (Continued)

| Item Description                 | Header  | Range         | Accuracy | Environment | IC Type | gage | Recording and Readout Required | Stylo Chart | Remarks |
|----------------------------------|---------|---------------|----------|-------------|---------|------|--------------------------------|-------------|---------|
| <b>Fig. Oil Flow</b>             |         |               |          |             |         |      |                                |             |         |
| Test Brg. No.1 Oil Flow          | POF1    | 1-10 ppm      |          |             |         |      |                                |             |         |
| Test Brg. No.2 Oil Flow          | BOF2    | 1-10 ppm      |          |             |         |      |                                |             |         |
| <b>Rig Pressures</b>             |         |               |          |             |         |      |                                |             |         |
| Axial Load Press.                | ALP     | 0-100 psig    |          |             |         |      |                                |             |         |
| Brg. No.1 Oil Supply Press.      | BOSPI   | 0-100 psig    |          |             |         |      |                                |             |         |
| Brg. No.1 Oil Sump Press.        | BSPI1   | ±15 psig      |          |             |         |      |                                |             |         |
| Brg. No.2 Oil Supply Press.      | BOISP2  | 0-100 psig    |          |             |         |      |                                |             |         |
| Brg. No.2 Oil Sump Press.        | BSPI2   | ±15 psig      |          |             |         |      |                                |             |         |
| Rig Oil Supply Press.            | ROISP   | 0-100 psig    |          |             |         |      |                                |             |         |
| <b>Rig Vibrations</b>            |         |               |          |             |         |      |                                |             |         |
| Rig Horz. Vibs Brg. No.2         | RHV1    | 0-10 mil      |          |             |         |      |                                |             |         |
| Rig Horz. Vibs Brg. No.1         | RHV2    | 0-10 mil      |          |             |         |      |                                |             |         |
| Rig Vert. Vibs Brg. No.2         | RVV1    | 0-10 mil      |          |             |         |      |                                |             |         |
| Rig Vert. Vibs Brg. No.1         | RVV2    | 0-10 mil      |          |             |         |      |                                |             |         |
| <b>Rig Speeds</b>                |         |               |          |             |         |      |                                |             |         |
| Shaft Speed                      | N2      | 0-100,000 rpm |          |             |         |      |                                |             |         |
| Brg. No.2 Cage Speed             | BZCS    | 0-45,000 rpm  |          |             |         |      |                                |             |         |
| <b>Turbine Temperatures</b>      |         |               |          |             |         |      |                                |             |         |
| Turb. Brg. No.1 Outer Race Temp. | TBRT1-1 | Amb-1000°F    | ±5°F     |             |         |      |                                |             |         |
| Turb. Brg. No.1 Outer Race Temp. | TBRT1-2 | Amb-1000°F    | ±5°F     |             |         |      |                                |             |         |
| Turb. Brg. No.2 Outer Race Temp. | TBRT2-1 | Amb-1000°F    | ±5°F     |             |         |      |                                |             |         |
| Turb. Brg. No.2 Outer Race Temp. | TBRT2-2 | Amb-1000°F    | ±5°F     |             |         |      |                                |             |         |
| Turb. Oil Inlet Temp. No.1       | TOIT1   | Amb-1000°F    | ±5°F     |             |         |      |                                |             |         |
| Turb. Oil Inlet Temp. No.2       | TOIT2   | Amb-1000°F    | ±5°F     |             |         |      |                                |             |         |
| Turb. Oil Scavenging Temp. No.1  | TOOT1   | Amb-1000°F    | ±5°F     |             |         |      |                                |             |         |
| Turb. Oil Scavenging Temp. No.2  | TOOT2   | Amb-1000°F    | ±5°F     |             |         |      |                                |             |         |
| Steam Inlet Temp.                | SIT     | Amb-1000°F    | ±5°F     |             |         |      |                                |             |         |
| Turbine Exhaust Temp.            | SOT     | Amb-1000°F    | ±5°F     |             |         |      |                                |             |         |
| <b>Turbine Pressures</b>         |         |               |          |             |         |      |                                |             |         |
| Steam Inlet Press.               | SIP     | 0-100 psig    |          |             |         |      |                                |             |         |
| Steam Exit Press.                | SOP     | 0-100 psig    |          |             |         |      |                                |             |         |
| Oil Inlet Press.                 | TOIP    | 0-30 psig     |          |             |         |      |                                |             |         |
| Turb. Seal Dam Air No.1          | TSDAI   | 0-30 psig     |          |             |         |      |                                |             |         |
| Turb. Seal Dam Air No.2          | TSDA2   | 0-30 psig     |          |             |         |      |                                |             |         |
| Turbine Oil Flow                 | TOP     | 1-10 ppm      |          |             |         |      |                                |             |         |
| Turbine Speed                    | TRPM    | 0-10,000 rpm  |          |             |         |      |                                |             |         |
| Turbine Horz. Vibs               | THV     | 0-10 mil      |          |             |         |      |                                |             |         |
| Turbine Vert. Vibs               | TVV     | 0-10 mil      |          |             |         |      |                                |             |         |

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**LOG OF ENGINE TEST**  
**EXPERIMENTAL TEST DEPARTMENT**

Sheet No.: A-  
Date: 2-23-78  
Engineer: J. Mohn

Stand D-3 Engine/Rig F33836 Build 6 Project 110X-20-200.XX  
Type of Test Oil Starvation — M-50 Steel Ball Bearing

| Position No. | a.m.<br>p.m. | Total<br>Hours | Rig Temperatures |        |        |        |        |        |        |        |        |        |        |        |
|--------------|--------------|----------------|------------------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|
|              |              |                | BAT1-3           | BAT1-1 | BAT1-2 | BAT1-4 | BAT2-3 | BAT2-2 | BAT2-4 | BAT2-1 | BAT2-2 | BAT2-1 | BATP-1 | BATP-2 |
| 1290         | 244          | 251            | 251              | 148    | 249    | 248    | 250    | 244    | 244    | 147    | 238    | 243    | 243    | 248    |
| 1404         | 242          | 252            | 252              | 153    | 251    | 252    | 252    | 244    | 244    | 152    | 240    | 245    | 246    | 241    |
| 1410         | 239          | 249            | 250              | 150    | 247    | 247    | 247    | 249    | 249    | 149    | 237    | 241    | 242    | 237    |

**LOG OF ENGINE TEST**  
**EXPERIMENTAL TEST DEPARTMENT**

Sheet No.: B-  
Date: 2-23-78  
Engineer: J. Mohn

Stand D-3 Engine/Rig F33836 Build 6 Project 110X-20-200.XX  
Type of Test Oil Starvation — M-50 Steel Ball Bearing

| Position No. | a.m.<br>p.m. | Total<br>Hours | Rig Temperatures |        |        |        |        |        |        |        |        |       |       |     |
|--------------|--------------|----------------|------------------|--------|--------|--------|--------|--------|--------|--------|--------|-------|-------|-----|
|              |              |                | IFT-2            | IFT-2A | IFT-2B | IFT-4A | IFT-4B | IFT-5A | IFT-5B | IFT-5A | IFT-5B | FPT-1 | FPT-2 | OTT |
| 1290         | 227          | 202            | 203              | 185    | 182    | 185    | 179    | 242    | 243    | 191    | 190    | 161   | 245   | 222 |
| 1404         | 241          | 209            | 209              | 187    | 184    | 178    | 246    | 244    | 198    | 197    | 196    | 167   | 246   | 221 |
| 1410         | 237          | 193            | 198              | 185    | 183    | 177    | 211    | 211    | 188    | 196    | 196    | 164   | 243   | 219 |

**LOG OF ENGINE TEST  
EXPERIMENTAL TEST DEPARTMENT**

Sheet No.: C  
Date: 2-23-78  
Engineer: J. Mohn

Stand D-3    Engine/Rig    F32836    Build    6    Project    110X-20-200-XX  
Type of Test    Oil Starvation — M-50 Steel Ball Bearing

| Position No. | Time |      | Rig Temperatures |         |         |         | Oil Flow |        | Turb Flow |     | Speed |       |      |       |                |        |        |        |
|--------------|------|------|------------------|---------|---------|---------|----------|--------|-----------|-----|-------|-------|------|-------|----------------|--------|--------|--------|
|              | a.m. | p.m. | Total Hours      | TBRT1-1 | TBRT1-2 | TBRT2-1 | TBRT2-2  | T01T-1 | T01T-2    | S/T | S/T   | B/OF1 | TOF  | T-RPM | N <sub>2</sub> | B2CS1  |        |        |
| 1200         | 214  | 214  | 41               | 42      | 43      | 44      | 45       | 46     | 47        | 48  | 49    | TRP4  | TOP3 | TOP2  | TOP1           | BOT2   | BUT1   |        |
| 1404         | 215  | 215  | 203              | 204     | 204     | 152     | 150      | 148    | 147       | 146 | 226   | 211   | 4.0  | 3.9   | 3.9            | 62,900 | 62,800 | 27,600 |
| 1410         | 215  | 215  | 203              | 203     | 203     | 151     | 150      | 148    | 147       | 146 | 226   | 212   | 4.0  | 3.9   | 4.0            | 62,900 | 62,800 | 28,400 |
|              |      |      |                  |         |         |         |          |        |           | 229 | 211   | 4.0   | 4.0  | 4.0   | 62,100         | 62,100 | 27,300 |        |

**LOG OF ENGINE TEST  
EXPERIMENTAL TEST DEPARTMENT**

Stand D-3    Engine/Rig    F32836    Build    6    Project    110X-20-200-XX  
Type of Test    Oil Starvation — M-50 Steel Ball Bearing

| Position No. | Time |      | Rig Pressures |        |        |       | Turbine Pressure |      | Rig Vibrations |        | Turbine Vibrations |       |       |     |     |  |
|--------------|------|------|---------------|--------|--------|-------|------------------|------|----------------|--------|--------------------|-------|-------|-----|-----|--|
|              | a.m. | p.m. | RALP          | BGSP-1 | BGSP-2 | BSP-1 | BSP-2            | SEP  | T01D-1         | TSDA-1 | TSDA-2             | RHV-1 | RHV-2 | THV | TVV |  |
| 1200         | 37   | 11.5 | 29            | 0      | 0      | 0     | 0                | 16   | 6              | 8      | 4                  | 0     | 0     | 0   | 0   |  |
| 1404         | 38   | 11.5 | 22.5          | 0      | 0      | 0     | 0                | 21.5 | 6              | 3      | 4                  | 0     | 0     | 0   | 0   |  |
| 1410         | 38   | 11.5 | 29.5          | 0      | 0      | 0     | 0                | 15   | 7              | 8      | 4                  | 0     | 0     | 0   | 0   |  |

**Pratt & Whitney Aircraft Group**  
**FR-11012**

**LOG OF COMPONENT TEST  
EXPERIMENTAL TEST DEPARTMENT**

| Stand No. 403 |                                      |                   |                            |    |          |
|---------------|--------------------------------------|-------------------|----------------------------|----|----------|
| Unit Name     | High Speed Bearing                   | Baro Pressure     | in. HG                     |    | °F       |
| Serial No.    | 35536-7                              | Fluid Type        | Mobil Jet II (MIL-L-29569) |    |          |
| Part No.      |                                      | Sp. Gravity       |                            | at | °F       |
| Type Test     | Oil Starvation S/N. P-11 Brz. S/N 10 | Sid Gage Cal Date |                            |    |          |
| Flowmeter S/N | Size                                 | Range             | Preset                     |    | Cal Date |

| Test Limits |       | Speeds - rpm          |           |        |        | Fouling - ppm |        |        |        | Pressures - psig |        |        |        |
|-------------|-------|-----------------------|-----------|--------|--------|---------------|--------|--------|--------|------------------|--------|--------|--------|
|             |       | Turbine Speed         | Boiler N. | Boiler | Boiler | Boiler        | Boiler | Boiler | Boiler | Boiler           | Boiler | Boiler | Boiler |
| Time        | Hours | T <sub>22</sub>       | BOT4      | 1      | 2      | 3             | 4      | 1      | 2      | 3                | 4      | 1      | 2      |
| (55.50)     | 2     | Start                 | 0         | 0      | 0      | 0             | 0      | 0      | 0      | 0                | 0      | 0      | 0      |
| 100.5       |       | 4,900                 | 4,940     | 4.0    | 4.0    | 3.9           | 8      | 32     | 37     | 0                | 0      | 6      | 35     |
| 161.5       |       | 63,400                | 61,050    | 25,600 | 4.0    | 4.1           | 4.0    | 7.5    | 31.5   | 37               | 0      | 7      | 8      |
| 130.6       |       | No. 2 Bearing Oil Off |           |        |        | Abort         |        |        |        | Stop             |        |        |        |
| 131.5       |       | 1.32 (RT)             |           |        |        | Stop          |        |        |        | Stop             |        |        |        |
| 132.0       |       |                       |           |        |        |               |        |        |        |                  |        |        |        |

**LOG OF COMPONENT TEST  
EXPERIMENTAL TEST DEPARTMENT**

|               |                                      |                   |                           |          |
|---------------|--------------------------------------|-------------------|---------------------------|----------|
| Unit Name     | High Speed Bearing                   | Baro Pressure     | in. HG                    | °F       |
| Serial No.    | 33926-7                              | Fluid Type        | Mobil Jet II (MIL-L-2639) |          |
| Part No.      |                                      | Sp. Gravity       | at                        | °F       |
| Type Test     | Oil Starvation S/N. Ball Brz. S/N 10 | Sed Gage Cal Date |                           |          |
| Flowmeter S/N | Size                                 | Range             | Preset                    | Cal Date |

Sheet No. B-2  
Date 05-07-73  
Engineer J. Mohn  
Operators Blake  
Stand No. 403

**LOG OF COMPONENT TEST**  
**EXPERIMENTAL TEST DEPARTMENT**

Unit Name High Speed Bearing Baro Pressure HC °F  
 Serial No. 33936-7 Fluid Type Mobil Jet II (MIL-L-23699)  
 Part No.  Sp. Gravity at °F  
 Type Test Oil Starvation SiN, Ball Brg. S/N 10 Sid Gage Cal Date

Flowmeter S/N  Size 1 Range 1 Preset  Cal Date

| Test<br>Limits |               | Temperatures - °F |     |     |     |                       |     |     |     |     |     |
|----------------|---------------|-------------------|-----|-----|-----|-----------------------|-----|-----|-----|-----|-----|
| Total          | Time<br>Hours | B470              | IFT | IFT | IFT | IFT                   | IFT | IFT | IFT | IFT | HCT |
| 2              | 2             | 24                | 23  | 44  | 54  | 54                    | 63  | 63  | 63  | 63  | 37  |
| 1045           | 2             | 76                | 78  | 78  | 78  | 78                    | 78  | 78  | 77  | 76  | 79  |
| 1045           | 139           | 114               | 116 | 115 | 117 | 128                   | 140 | 141 | 114 | 125 | 141 |
| 1046           | 233           | 263               | 264 | 187 | 178 | 239                   | 237 | 235 | 190 | 179 | 192 |
| 1219 5         |               |                   |     |     |     | No. 2 Bearing Oil Off |     |     |     |     |     |
|                |               |                   |     |     |     | Abort                 |     |     |     |     |     |

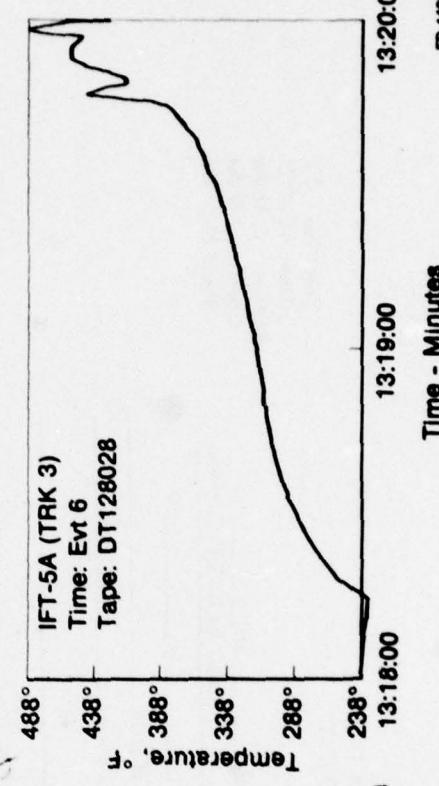
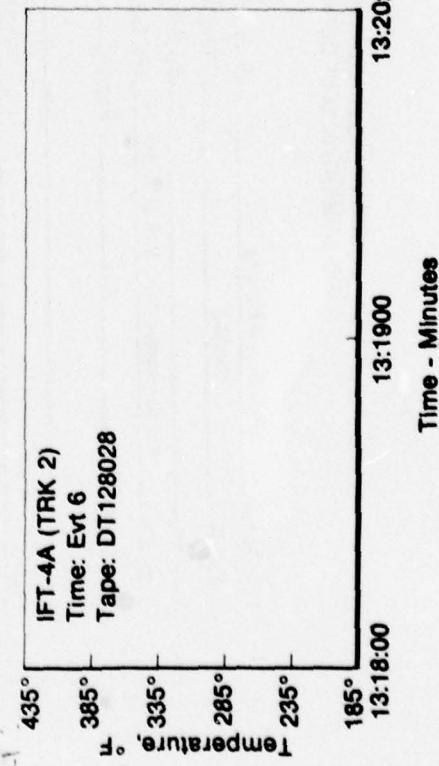
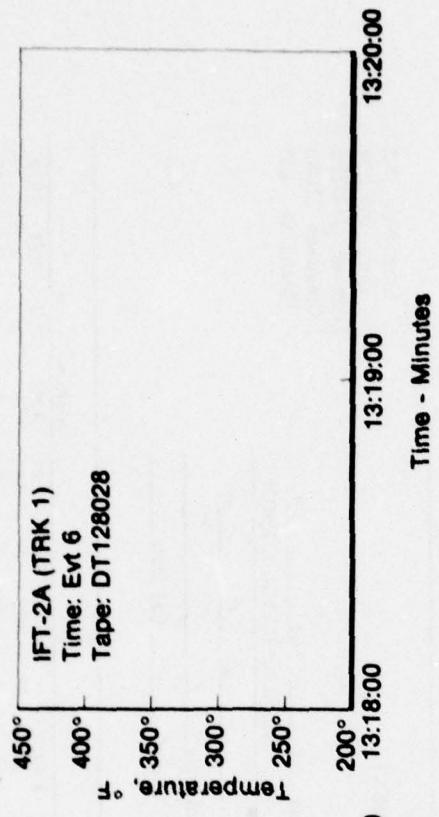
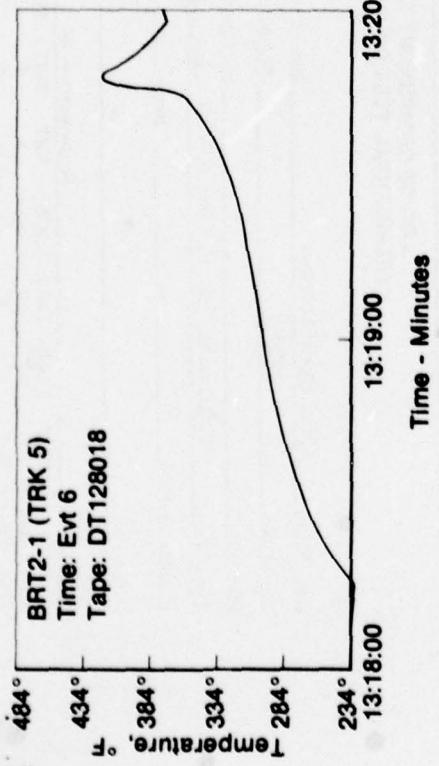
**LOG OF COMPONENT TEST**  
**EXPERIMENTAL TEST DEPARTMENT**

Unit Name High Speed Bearing Baro Pressure in. HG °F  
 Serial No. 33936-7 Fluid Type Mobil Jet II (MIL-L-23699)  
 Part No.  Sp. Gravity at °F  
 Type Test Oil Starvation SiN, Ball Brg. S/N 10 Sid Gage Cal Date

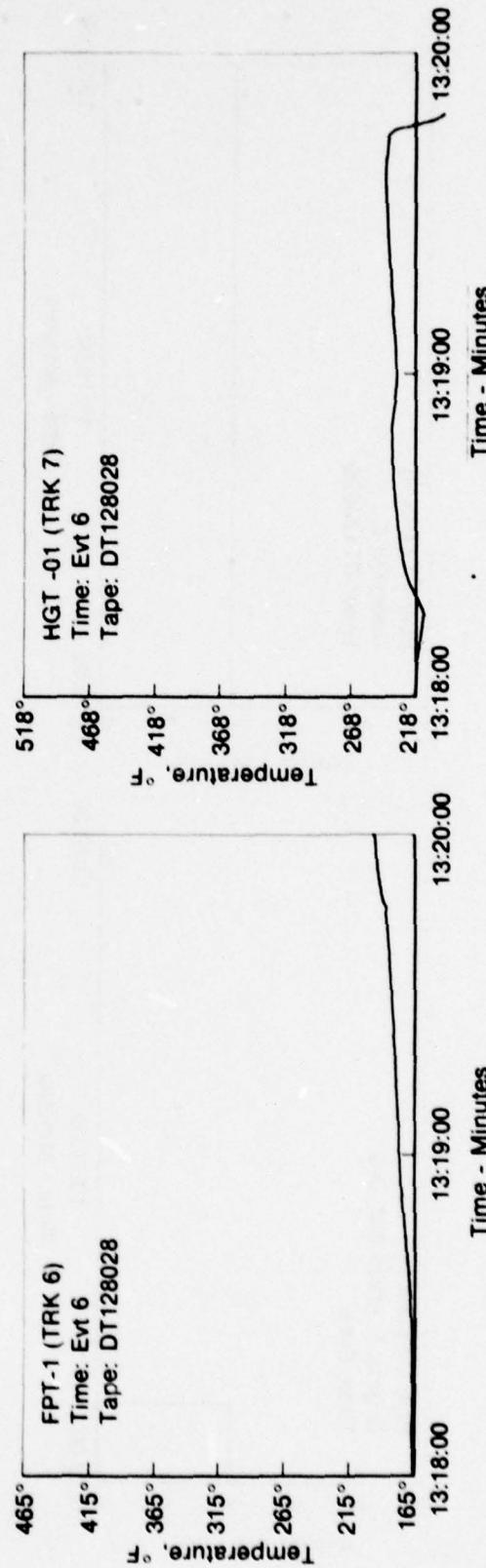
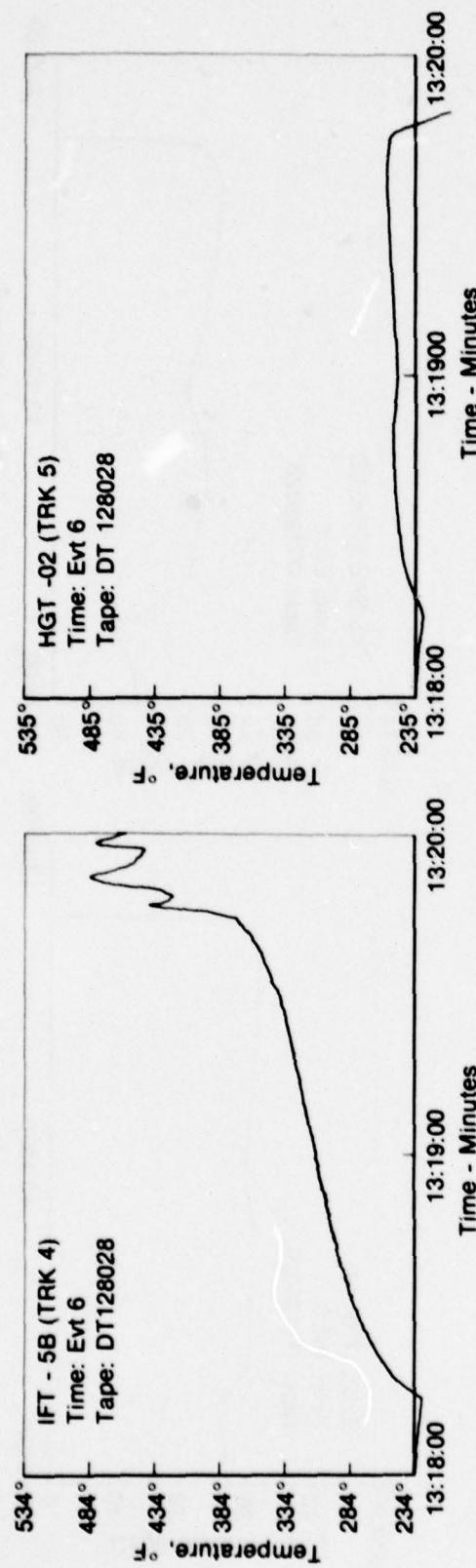
Flowmeter S/N  Size 1 Range 1 Preset  Cal Date

| Test<br>Limits |               | Temperatures - °F |      |      |                       |       |      |      |      |      |      | Vibrations - mils |     |     |     |
|----------------|---------------|-------------------|------|------|-----------------------|-------|------|------|------|------|------|-------------------|-----|-----|-----|
| Total          | Time<br>Hours | TH27              | TH27 | TH27 | TH27                  | TH27  | TH27 | TH27 | TH27 | TH27 | TH27 | VTH               | VTH | VTH | VTH |
| 1045           | 2             | 75                | 75   | 75   | 81                    | 81    | 86   | 86   | 79   | 79   | 0    | 1                 | 2   | 1   | 1   |
| 1045           | 166           | 165               | 156  | 157  | 142                   | 141   | 136  | 147  | 202  | 212  | 0    | 0                 | 0   | 0   | 0   |
| 1046           | 217           | 218               | 205  | 205  | 150                   | 150   | 150  | 151  | 237  | 213  | 0    | 0                 | 0   | 0   | 0   |
| 1219 5         |               |                   |      |      | No. 2 Bearing Oil Off |       |      |      |      |      |      |                   |     |     |     |
|                |               |                   |      |      |                       | Abort |      |      |      |      |      |                   |     |     |     |
|                |               |                   |      |      |                       | Stop  |      |      |      |      |      |                   |     |     |     |

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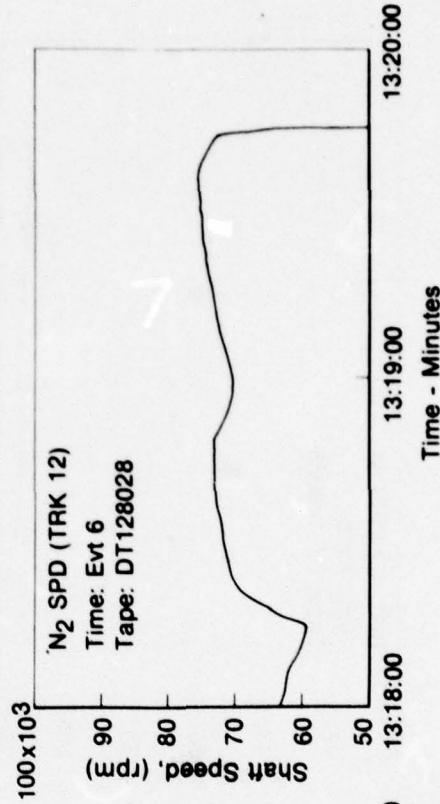
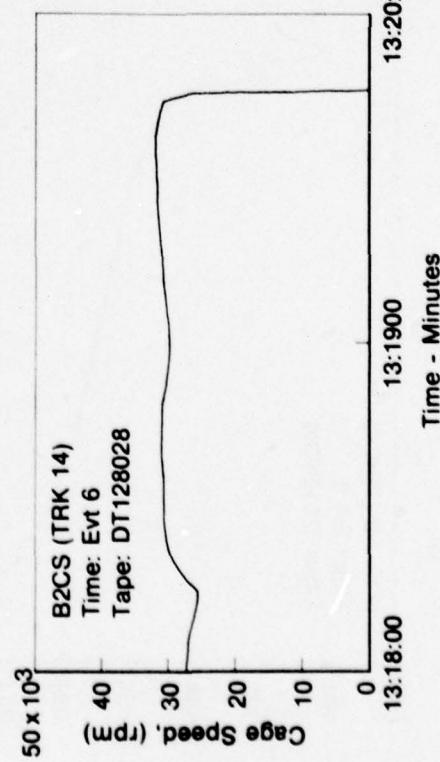
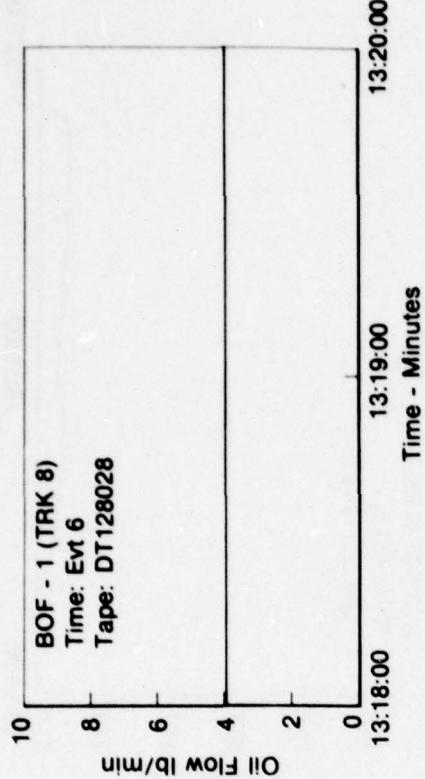
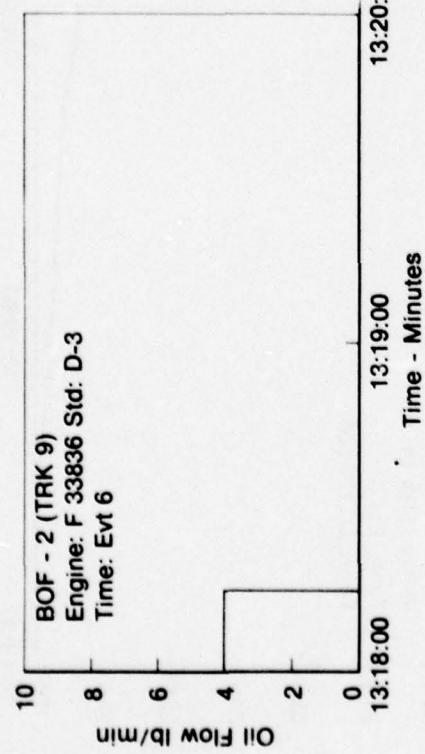


RD 14600



FD 14499

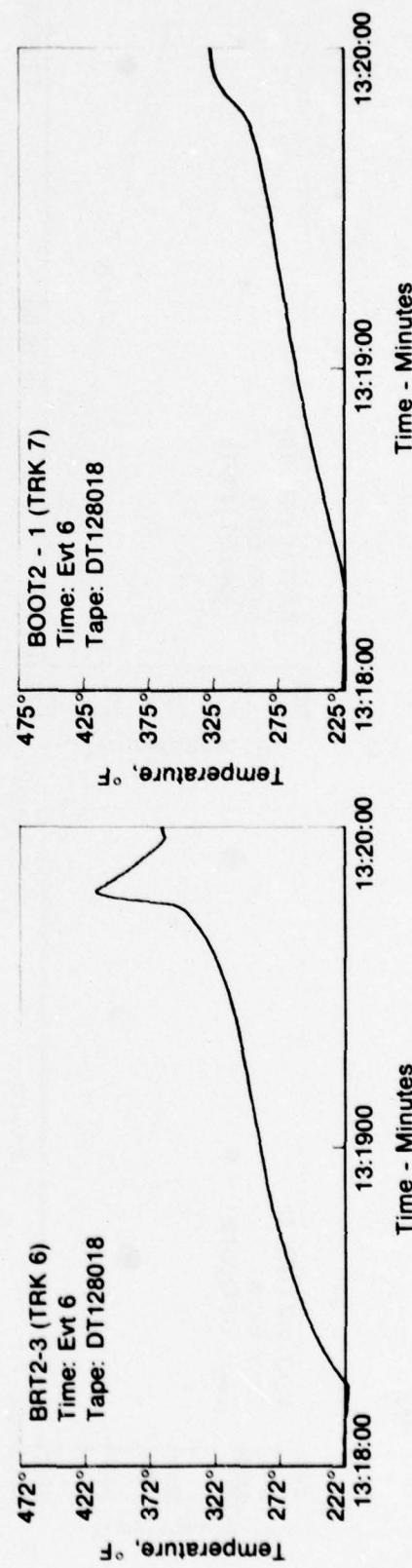
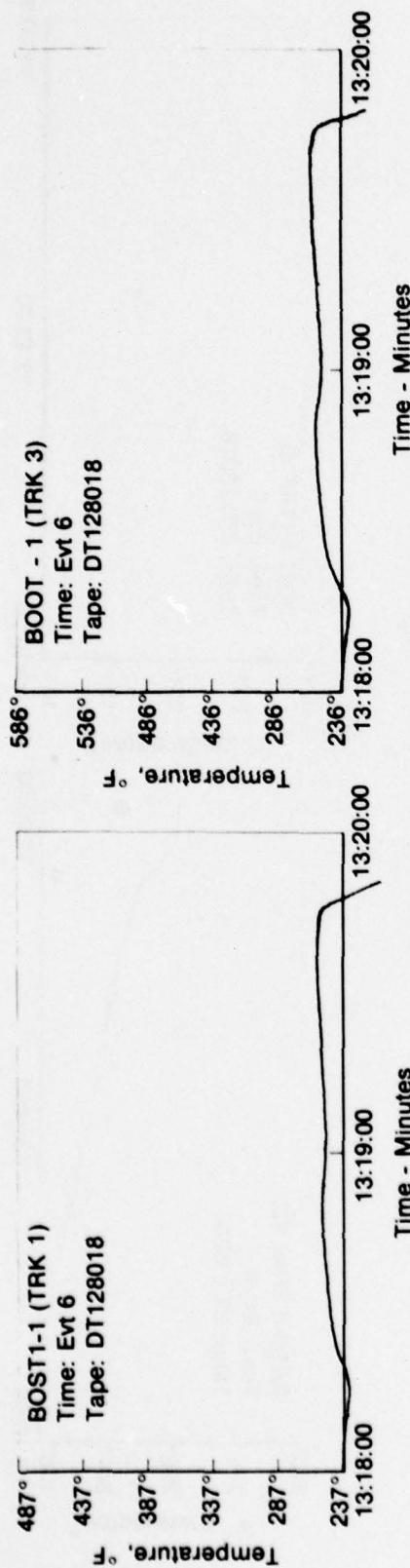
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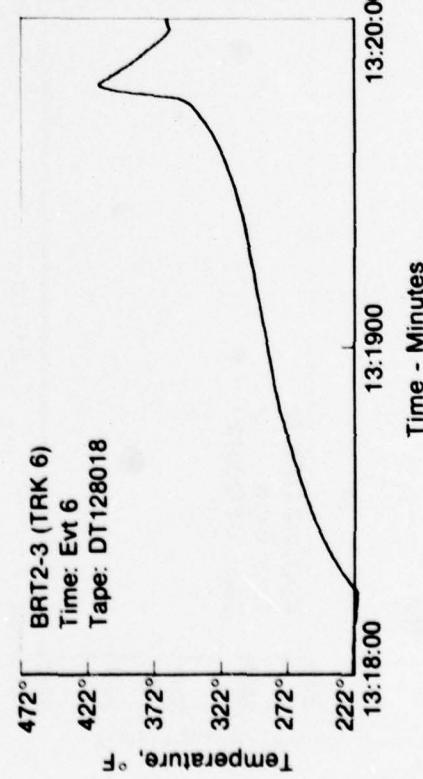
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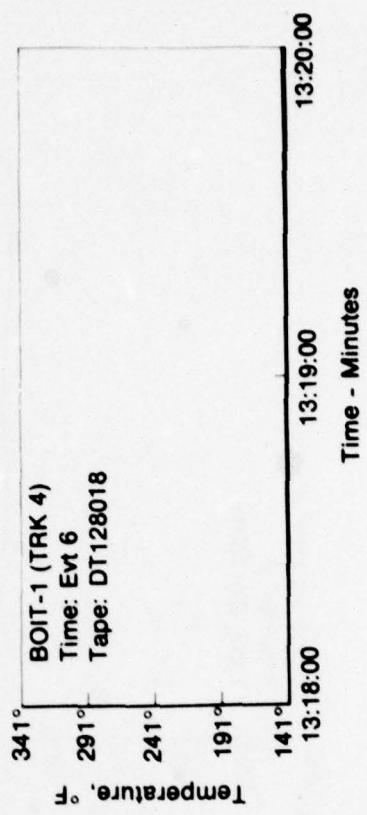
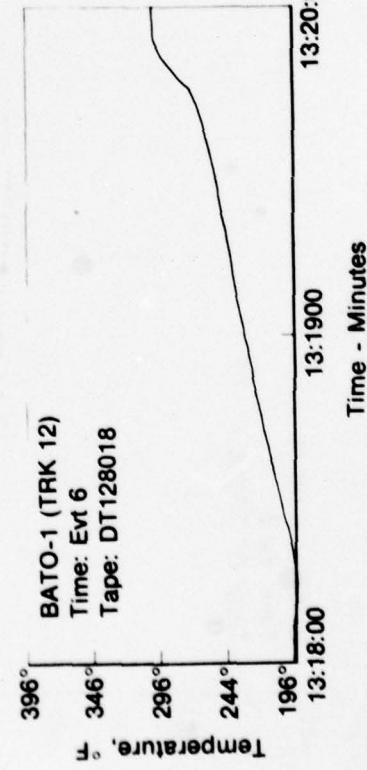
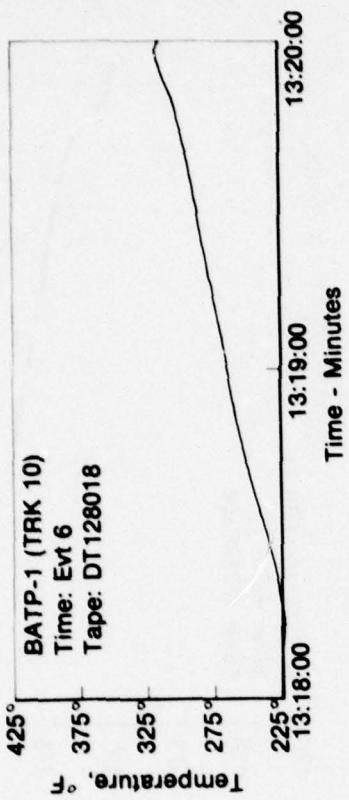
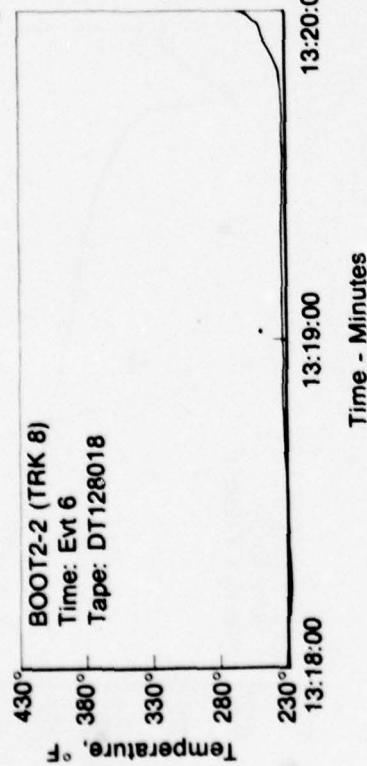


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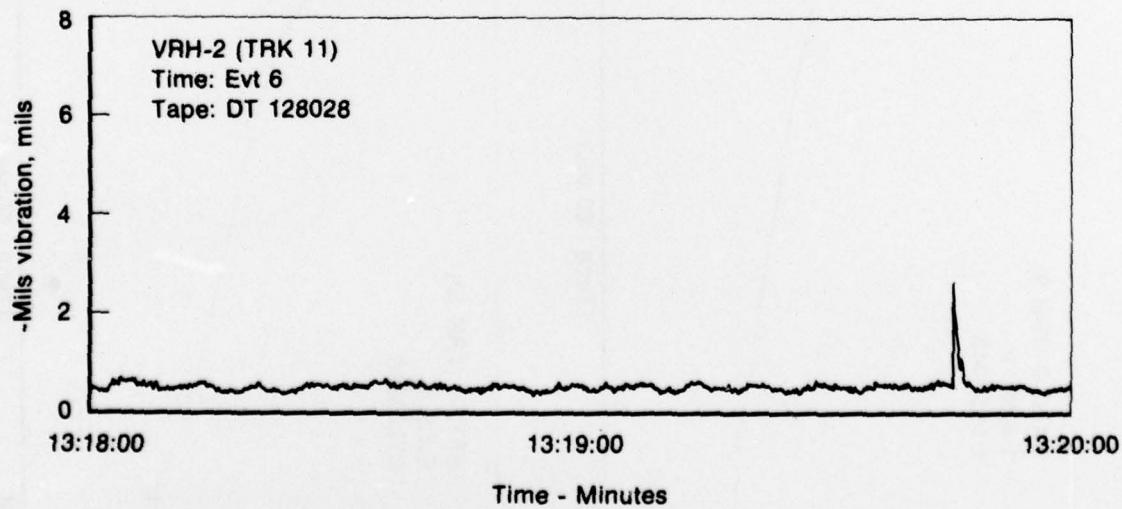
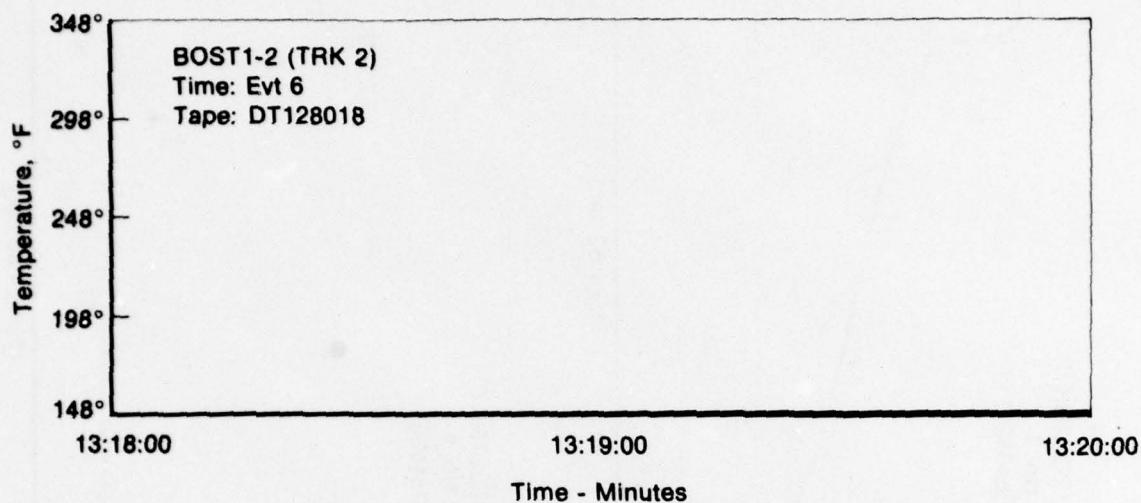
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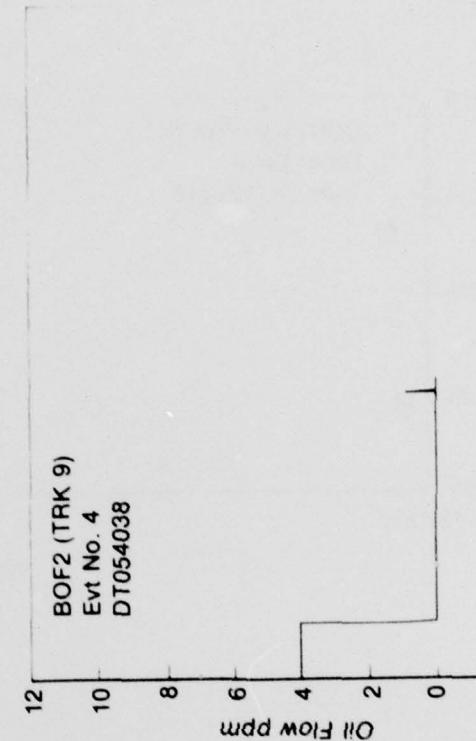
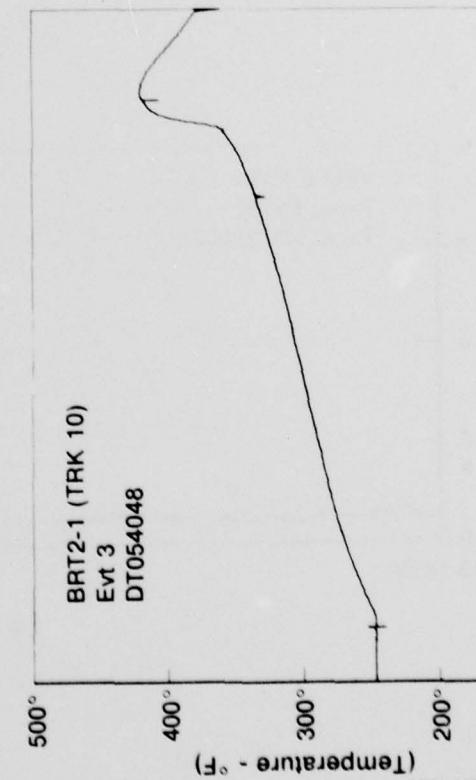
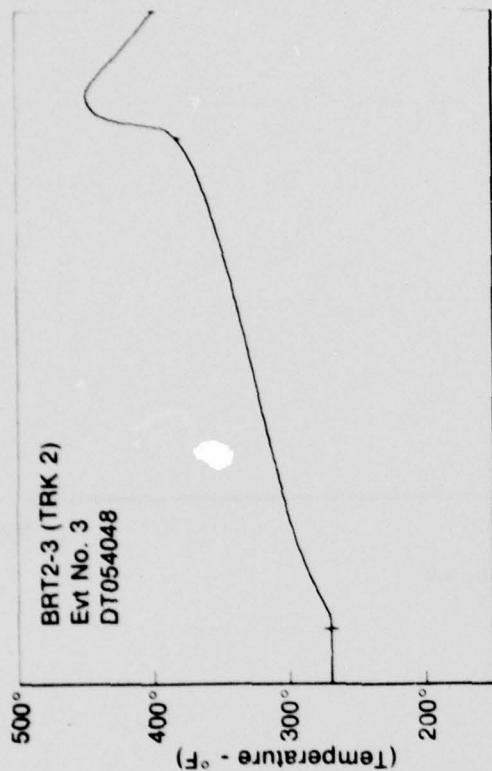
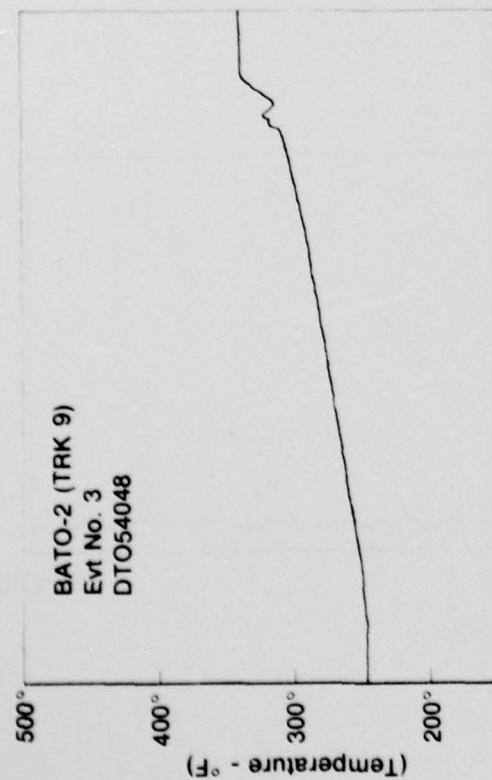
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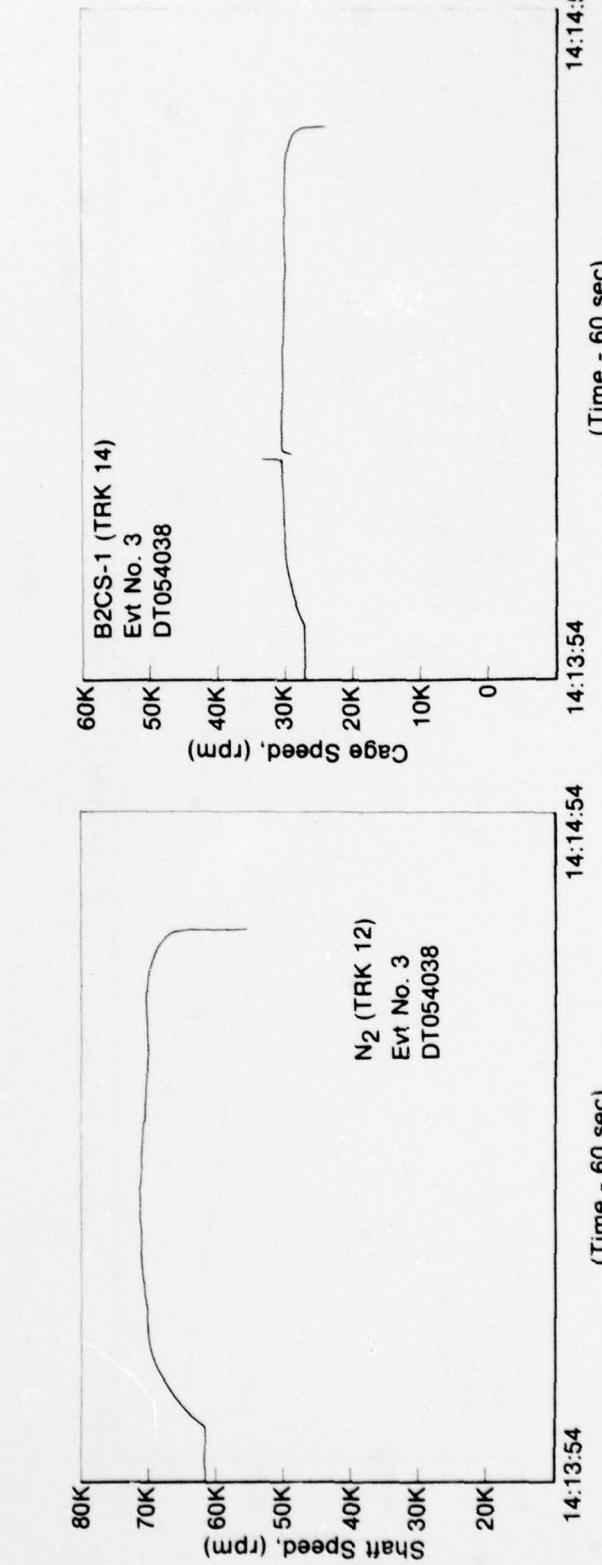
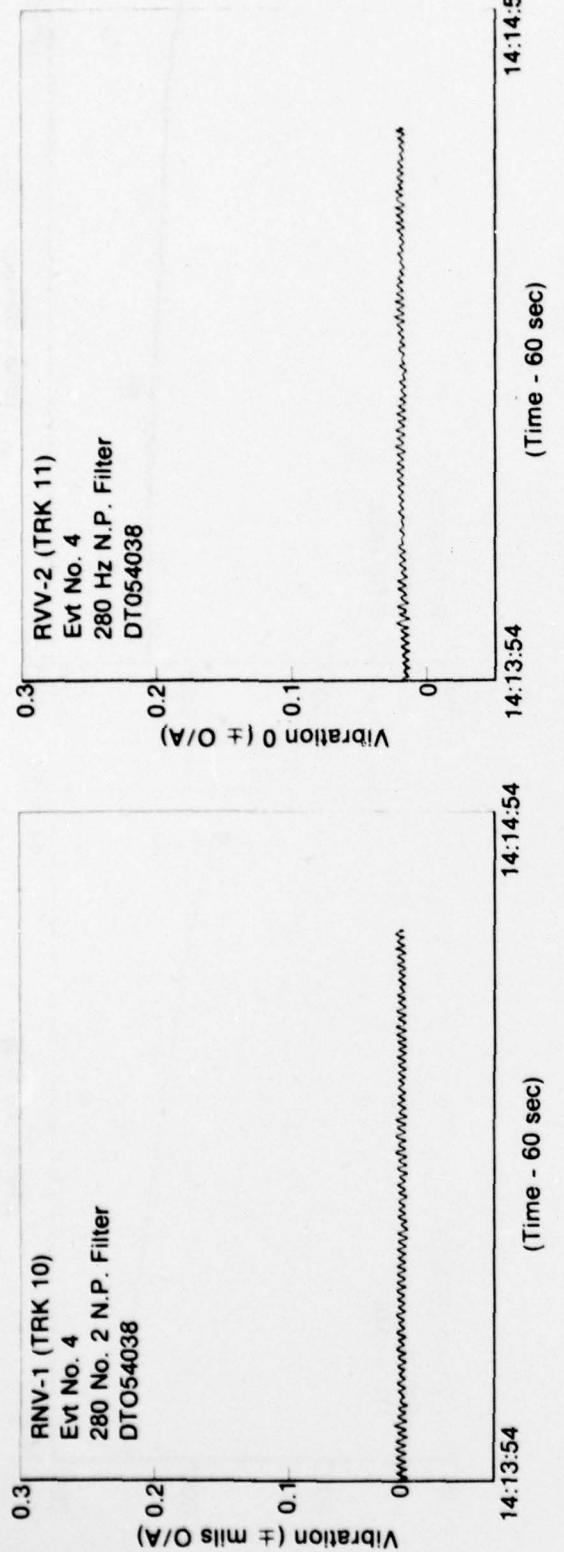


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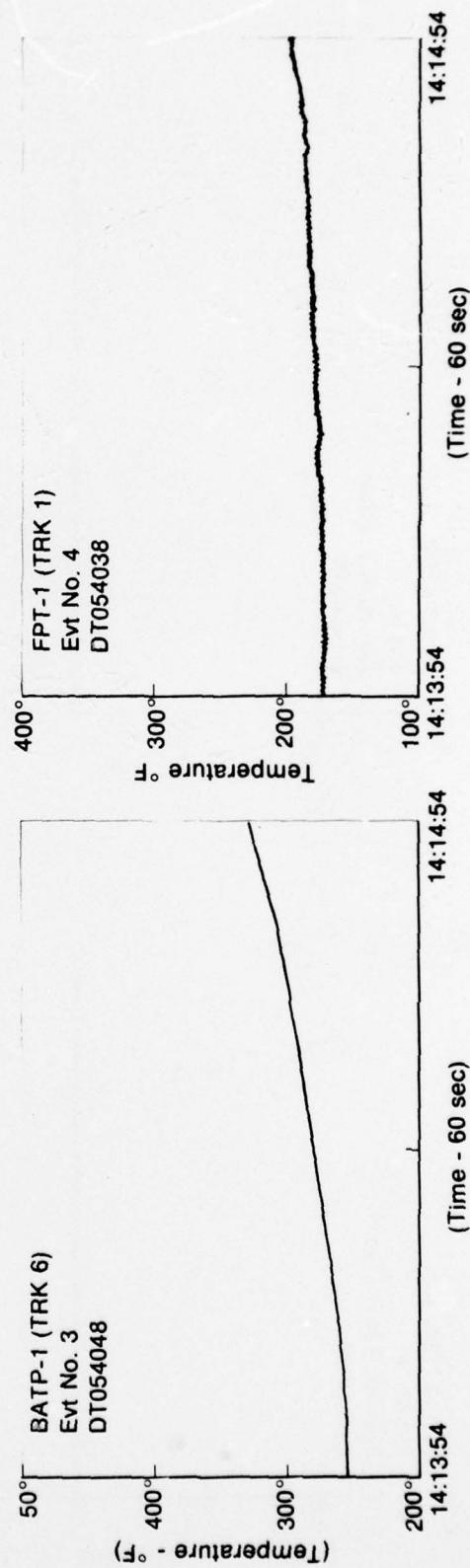
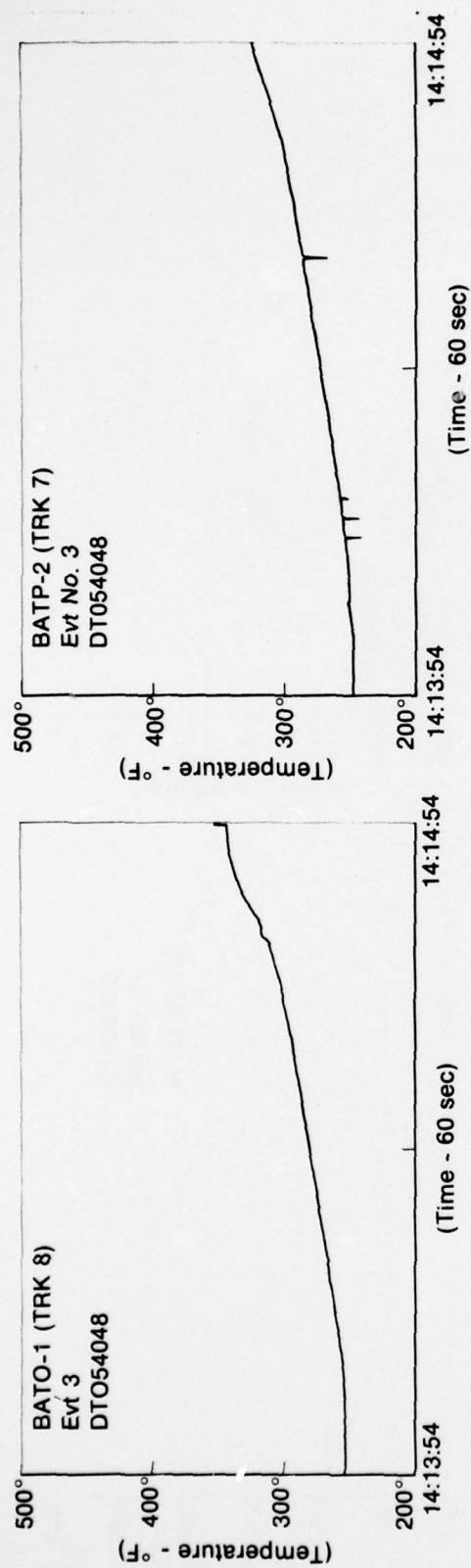
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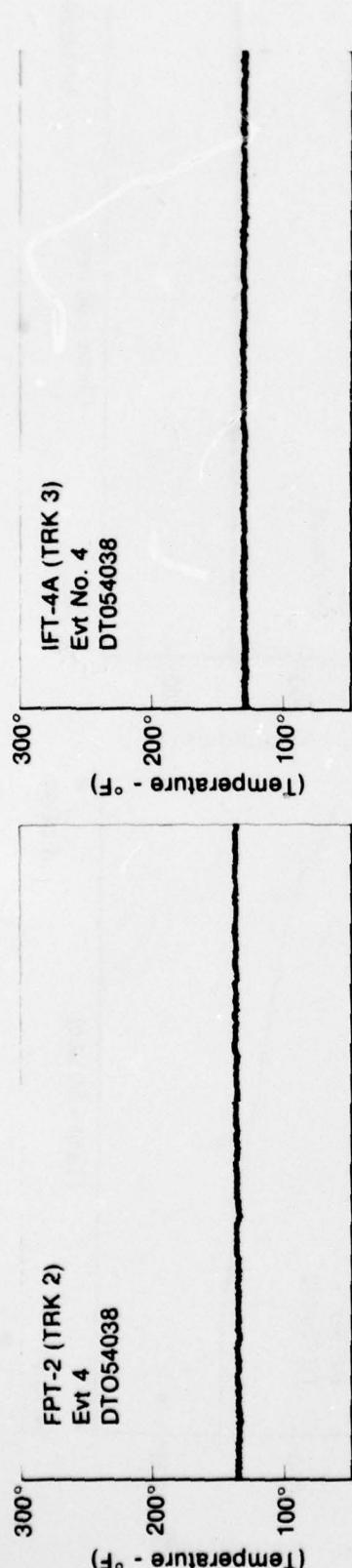


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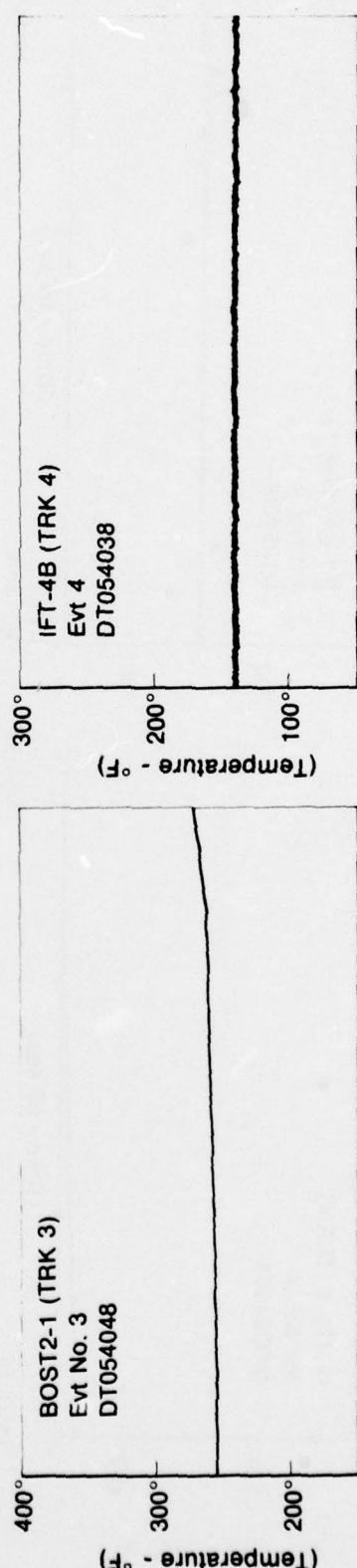


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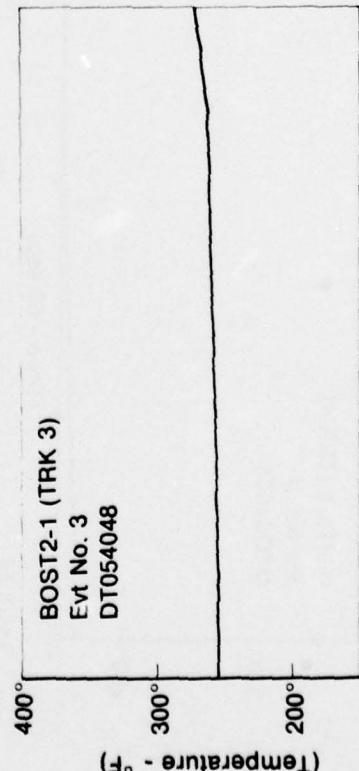
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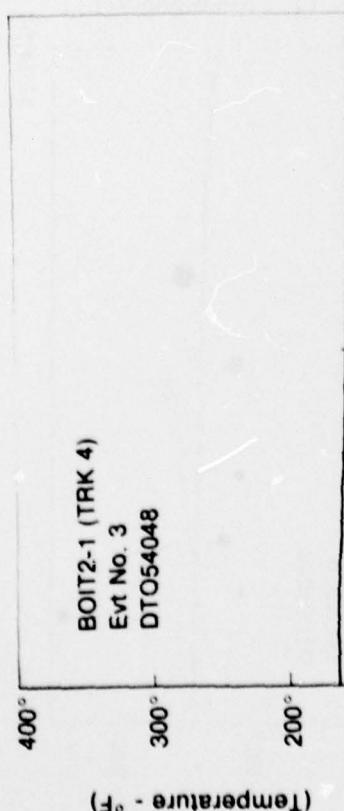


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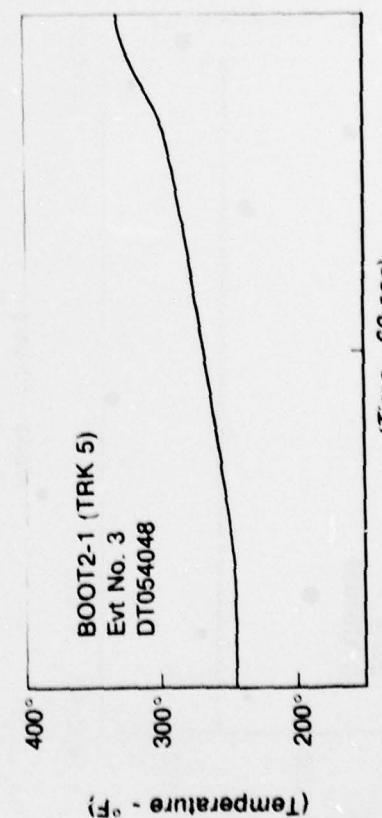


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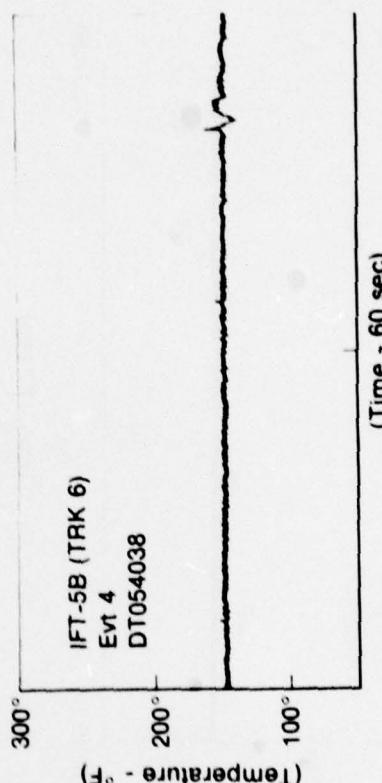
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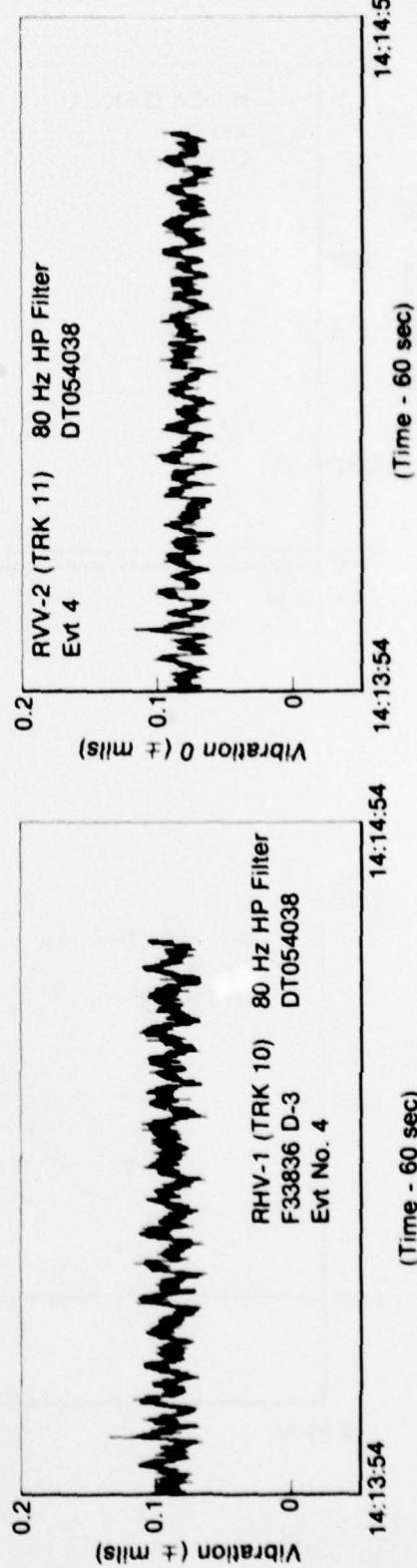
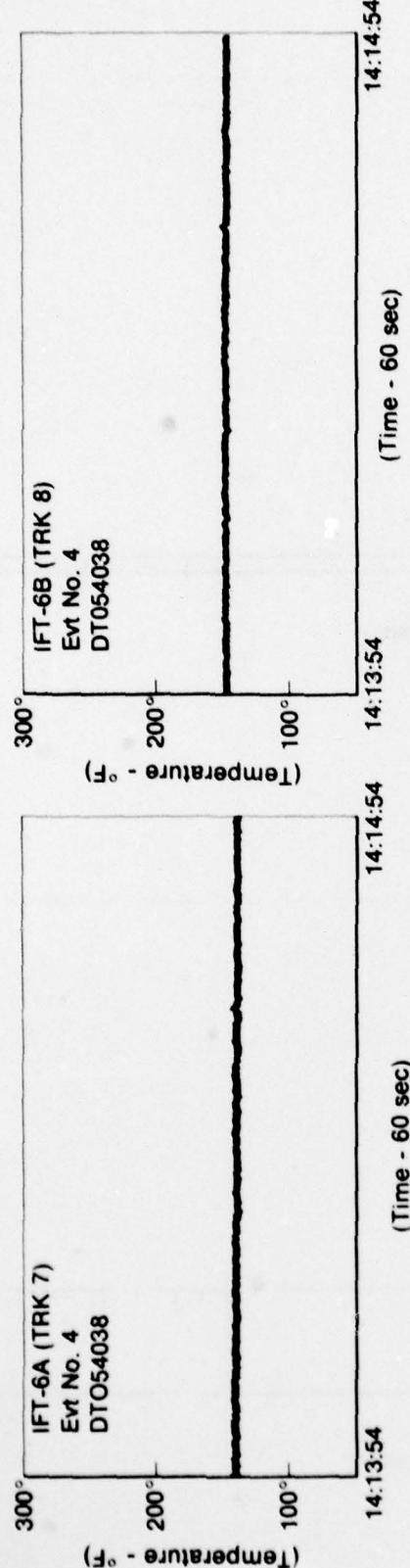
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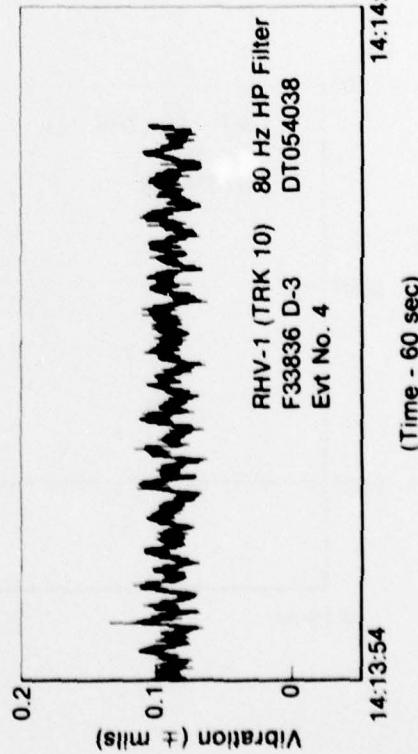
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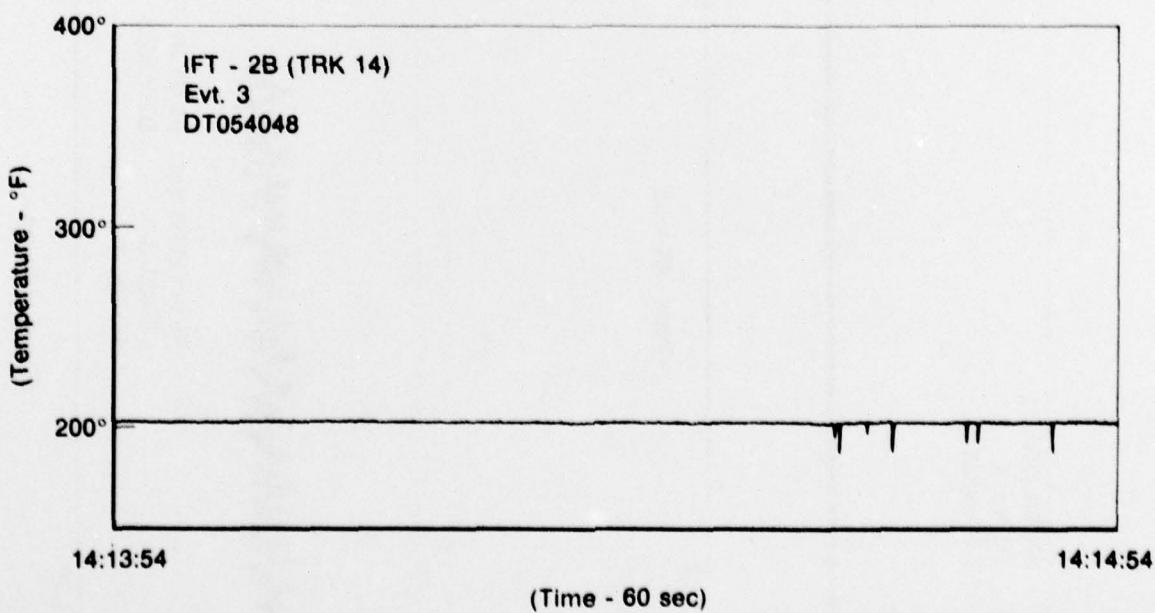
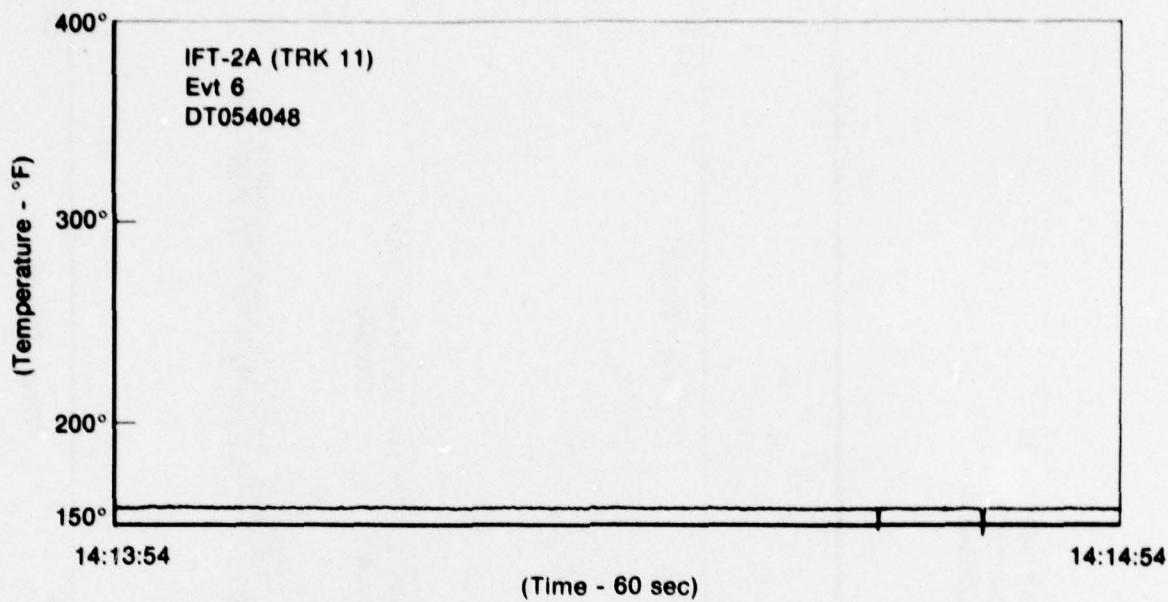
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